

SANDIA REPORT

SAND2014-20108

Unlimited Release

Printed November 2014

MB3a Infrasound Sensor Evaluation

B. John Merchant
Kyle D. McDowell

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



SAND2014-20108
Unlimited Release
Printed November 2014

MB3a Infrasound Sensor Evaluation

B. John Merchant
Kyle D. McDowell
Ground-Based Monitoring Research & Engineering
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0404

Abstract

Sandia National Laboratories has tested and evaluated a new infrasound sensor, the MB3a, manufactured by Seismo Wave. These infrasound sensors measure pressure output by a methodology developed by researchers at the French Alternative Energies and Atomic Energy Commission (CEA) and the technology was recently licensed to Seismo Wave for production and sales. The purpose of the infrasound sensor evaluation was to determine a measured sensitivity, transfer function, power, self-noise, dynamic range, seismic sensitivity, and self-calibration ability. The MB3a infrasound sensors are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

ACKNOWLEDGMENTS

This work was funded by the United States Department of State as a CTBT Contribution-in-Kind with the support of the Department of Energy Office of Nuclear Verification (NA-243).

We would like to thank CEA for providing the MB3a sensors to evaluate and Guillaume Nief and Phillipe Millier of CEA for their assistance in preparing for and performing the evaluation.

CONTENTS

1	Executive Summary	9
2	Testing Overview	11
2.1	Objectives	11
2.2	Test and Evaluation Background	11
2.3	Standardization and Traceability	11
2.4	Test and Evaluation Process	12
2.4.1	Infrasound Sensor Testing	12
2.4.2	General Infrasound Sensor Performance Tests	12
2.5	Test Configuration and System Specifications	13
2.5.1	Power	15
2.5.2	Data Recording	15
2.5.3	Signal Generation	15
2.5.4	Reference Sensors	16
2.5.5	Infrasound Sensor Configuration	16
2.5.6	Ambient Conditions	17
3	Evaluation	19
3.1	Power	19
3.2	Isolation Noise	20
3.3	Dynamic Range	21
3.4	Frequency Amplitude Response Verification	22
3.5	Frequency Amplitude Phase Verification	24
3.6	Dynamic Noise	28
3.7	Harmonic Distortion	29
3.8	2-Tone	30
3.9	Calibrator Frequency Amplitude Response Verification	33
3.10	Calibrator Frequency Amplitude Phase Verification	36
3.11	Calibrator Harmonic Distortion	42
3.12	Calibrator 2-Tone	43
3.13	Seismic Sensitivity	46
4	Evaluation Summary	51
	References	53
	Appendix A: Responses	55
	MB2000 Response	55
	MB2005 Response	56
	MB3a Response	57
	Distribution	58

FIGURES

Figure 1 MB3a Infrasound Sensors	9
Figure 2 Test Configuration Diagram.....	13
Figure 3 Isolation Chamber, MB2000 and MB2005 References, MB3a Sensors.....	14
Figure 4 GS13 Seismometer, Vaisala Pressure & Temperature Reference, and Piston-Phone ...	14
Figure 5 Ambient Pressure and Temperature	17
Figure 6 MB3a Isolation Time Series.....	20
Figure 7 MB3a Isolation Power Spectra.....	20
Figure 8 MB3a Isolation Incoherent Self-Noise.....	21
Figure 9 Piston-phone Tone Time Series for 1 Hz	23
Figure 10 Piston-phone White Noise Power Spectra	25
Figure 11 Piston-phone White Noise Coherence.....	25
Figure 12 Piston-phone White Noise Relative Magnitude, 0.02 – 4 Hz	26
Figure 13 Piston-phone White Noise Relative Phase, 0.02 – 4 Hz	26
Figure 14 Piston-phone White Noise Relative Magnitude, 0.01 – 28 Hz	27
Figure 15 Piston-phone White Noise Relative Phase, 0.01 – 28 Hz	27
Figure 16 MB3a Dynamic Noise Time Series.....	28
Figure 17 MB3a Dynamic Noise Power Spectra.....	29
Figure 18 MB3a Dynamic Noise Incoherent Noise	29
Figure 19 2-Tone Time Series	31
Figure 20 2-Tone Filtered Time Series.....	32
Figure 21 2-Tone Sensitivity MB3a SN52	33
Figure 22 2-Tone Sensitivity MB3a SN30	33
Figure 23 Calibrator Time Series Tones for 1 Hz	34
Figure 24 Calibrator White Noise Time Series	37
Figure 25 Calibrator White Noise Power Spectra	38
Figure 26 Calibrator White Noise Coherence	38
Figure 27 Calibrator White Noise Relative Magnitude, 0.02 – 4 Hz	38
Figure 28 Calibrator White Noise Relative Phase, 0.02 – 4 Hz	39
Figure 29 Calibrator Incoherent Noise	39
Figure 30 Calibrator White Noise Relative Magnitude, 0.01 – 28 Hz	40
Figure 31 Calibrator White Noise Relative Phase, 0.01 – 28 Hz	40
Figure 32 Calibrator White Noise MB3a vs MB3a Coherence.....	41
Figure 33 Calibrator White Noise MB3a vs MB3a Relative Magnitude, 0.1 – 28 Hz.....	41
Figure 34 Calibrator White Noise MB3a vs MB3a Relative Phase, 0.1 – 28 Hz.....	41
Figure 35 Calibrator Harmonic Distortion, 3 Pa	42
Figure 36 Calibrator Harmonic Distortion, 24 Pa	43
Figure 37 Calibrator 2-Tone Time Series.....	44
Figure 38 2-Tone Filtered Time Series.....	45
Figure 39 Calibrator 2-Tone Sensitivity MB3a SN52	46
Figure 40 Calibrator 2-Tone Sensitivity MB3a SN30	46
Figure 41 Pressure Time Series Due to Ground Motion	47
Figure 42 Pressure Power Spectra Due to Ground Motion	47
Figure 43 Ground Motion Coherence.....	48
Figure 44 Ground Motion Magnitude Relative to the GS13 Seismometer	49

Figure 45 Infrasound Sensor Seismic Sensitivity	49
Figure 46 Ground Motion Power Spectra	50
Figure 47 MB2000 Response	55
Figure 48 MB2005 Response	56
Figure 49 MB3a Response.....	57

TABLES

Table 1 Minimum requirements for station specifications	10
Table 2 Geotech Smart24 Digitizer S1036 Configuration	15
Table 3 Geotech Smart24 Digitizer S1043 Configuration	15
Table 4 MB3a Power Consumption	19
Table 5 MB3a RMS Noise and Dynamic Range.....	21
Table 6 Piston-phone Tone Amplitudes	22
Table 7 Piston-phone Tone Frequencies.....	22
Table 8 Piston-phone Sensitivities vs Pressure and Frequency for MB3a SN30	23
Table 9 Piston-phone Sensitivities vs Pressure and Frequency for MB3a SN52	24
Table 10 Piston-phone Average Sensitivities	24
Table 11 Piston-phone White Noise Relative Magnitude and Phase, 0.02 – 4 Hz.....	26
Table 12 Piston-phone White Noise Relative Magnitude and Phase, 0.01 – 28 Hz.....	27
Table 13 2-Tone Sensitivities	32
Table 14 Calibrator Tone Amplitudes	34
Table 15 Calibrator Tone Frequencies	34
Table 16 Calibrator Sensitivities vs Pressure and Frequency for MB3a SN30	35
Table 17 Calibrator Sensitivities vs Pressure and Frequency for MB3a SN52	35
Table 18 Calibrator Average Sensitivities	35
Table 19 Calibrator White Noise Relative Magnitude and Phase, 0.02 – 4 Hz	39
Table 20 Calibrator White Noise Relative Magnitude and Phase, 0.01 – 28 Hz	40
Table 21 Calibrator Harmonic Distortion, 3 Pa.....	42
Table 22 Calibrator Harmonic Distortion, 24 Pa.....	43
Table 23 Calibrator 2-Tone Sensitivities	45

NOMENCLATURE

CEA	French Alternative Energies and Atomic Energy Commission
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
dB	decibel
DOE	Department of Energy
IMS	International Monitoring System
LNM	Low Noise Model
PSD	Power Spectral Density
SNL	Sandia National Laboratories

1 EXECUTIVE SUMMARY



Figure 1 MB3a Infrasound Sensors

The evaluation of the two MB3a infrasound sensors, serial numbers 30 and 52, has identified that the sensors performance are consistent with their manufacturer's specifications.

The sensor self-noises are in agreement with the noise models from CEA and were measured to be entirely below the Bowman Low Noise Model (LNM). The MB3a self-noise was evaluated as being 36 dB below the noise level of $5 \text{ mPa}/\sqrt{\text{Hz}}$ at 1 Hz, exceeding the IMS requirement of being at least 18 dB below. In addition, the self-noise of the MB3a appears to be unchanged across a wide range of dynamic inputs. Using the measured self-noise and sensor clip level of ± 24 Volts, the dynamic range was estimated to be more than 115 dB across the 0.02 to 4 Hz pass band.

The MB3a SN30 and SN52 have a measured sensitivity at 1 Hz of 21.20 mV/Pa and 20.30 mV/Pa, respectively. This represents a difference from the 20 mV/Pa nominal sensitivity of 6% (0.51 dB) and 1.5% (0.13 dB). The responses of both the MB3a sensors are flat to pressure across the 0.02 to 4 Hz pass band to within 2.9% (0.25 dB) in magnitude and 0.6 degrees in phase. In addition, the sensor responses appear to be linear to within measurement error across a ± 12 Pa range of amplitudes.

The MB3a calibrator is able to be fed a variety of signals for the purpose of self-calibration. The results of using the calibrator to evaluate sensitivity, response, pass band, and linearity were consistent with the results obtained using a piston-phone and separate reference sensor.

The MB3a sensors have an evaluated seismic sensitivity of $0.6 \text{ V}/\text{m}/\text{s}^2$ which is consistent with the manufacturer's specification of $30 \text{ Pa}/\text{m}/\text{s}^2$ for a pressure sensitivity of 20 mV/Pa.

**Table 1 Minimum requirements for station specifications
(from CTBT/PC/III/1/Add.2/Appendix X)**

Characteristics	Minimum Requirements	MB3a SN 30	MB3a SN 52
<i>Sensor Type</i>	Microbarometer	Microbarometer	Microbarometer
<i>Number of sensors</i>	4-element array ¹		
<i>Geometry</i>	Triangle with a component at the centre		
<i>Spacing</i>	Triangle basis: 1 to 3 km ²		
<i>Station location accuracy</i>	≤100m		
<i>Relative sensor location</i>	≤1 m		
<i>Measured parameter</i>	Absolute ³ or differential pressure	Absolute and differential, only absolute output evaluated	Absolute and differential, only absolute output evaluated
<i>Passband</i>	0.02 to 4 Hz	0.01 to 28 Hz	0.01 to 28 Hz
<i>Sensor response</i>	Flat to pressure over the passband		
<i>Sensor noise</i>	≤ 18 dB below minimum acoustic noise ⁴	36 dB below minimum acoustic noise	36 dB below minimum acoustic noise
<i>Calibration</i>	≤5% in absolute amplitude ⁵		
<i>State of health</i>	Status data transmitted to the International Data Center		
<i>Sampling rate</i>	≥ 10 samples per second		
<i>Resolution</i>	≥ 1 count per 1 mPa	8.908 counts/mPa (21.20 mV/Pa with a 40 Vpp 24-bit digitizer)	8.529 counts/mPa (20.30 mV/Pa with a 40 Vpp 24-bit digitizer)
<i>Dynamic range</i>	≥ 108 dB	115 dB	115 dB
<i>Timing Accuracy</i>	≤1 ms ⁶		
<i>Standard temperature range</i>	-10°C to +45°C ⁷	Evaluated at approximately 26°C	Evaluated at approximately 26°C
<i>Buffer at station or at National Data Center</i>	≥7 days		
<i>Data format</i>	Group of Scientific Expert format		
<i>Data frame length</i>	≤30 seconds		
<i>Data transmission</i>	Continuous		
<i>Data availability</i>	≥98 %		
<i>Timely data availability</i>	≥97 %		
<i>Mission-capable array</i>	≥3 elements operational		
<i>Acoustic filtering</i>	Noise reduction pipes (site dependent)		
<i>Auxiliary data</i>	Meteorological data ⁸		

¹ In case of noisy sites or when increased capability is required, number of components could be increased.

² 3 km is the recommended spacing.

³ Used for daily state of health.

⁴ Minimum noise level at 1 Hz : - ~5 mPa.

⁵ Periodicity : once per year (minimum).

⁶ Better than or equal to 1 ms.

⁷ Temperature range to be adapted for some specific sites.

⁸ Once per minute

2 TESTING OVERVIEW

2.1 Objectives

The objective of this work was to evaluate the overall technical performance of the MB3a infrasound sensor. The MB3a is a recent infrasound sensor developed by CEA, expanding upon the prior MB2000 and MB2005 sensors. Notable features of the MB3a include a change in the transducer from an LVDT to a magnet and coil, the ability to perform calibrations, and a significant reduction in the size of the sensor. Basic infrasound sensor characterization includes determining sensitivity, linearity to pressure input, power, self-noise, full-scale, 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 MB2005 infrasound sensor used in this testing has been evaluated using Los Alamos National Laboratories calibrated reference chamber to determine its sensitivity. The MB2000 used in this testing was subsequently evaluated against the MB2005. In addition, after the testing of the MB3a's was performed, a static pressure calibration of both the MB2000 and MB2005 was performed at Sandia using a Keller portable calibrator which determined the MB2000 and MB2005 sensitivities to be correct to within 1%.

2.4 Test and Evaluation Process

2.4.1 *Infrasound Sensor Testing*

Testing of the MB3a sensors was performed on July 21 – 24, 2014, 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)

In addition, because the MB3a contains a self-calibration input, many of the above tests were run twice: Once with the piston-phone generating a pressure input and again with the generated voltage signal inputted to the calibrator.

2.5 Test Configuration and System Specifications

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

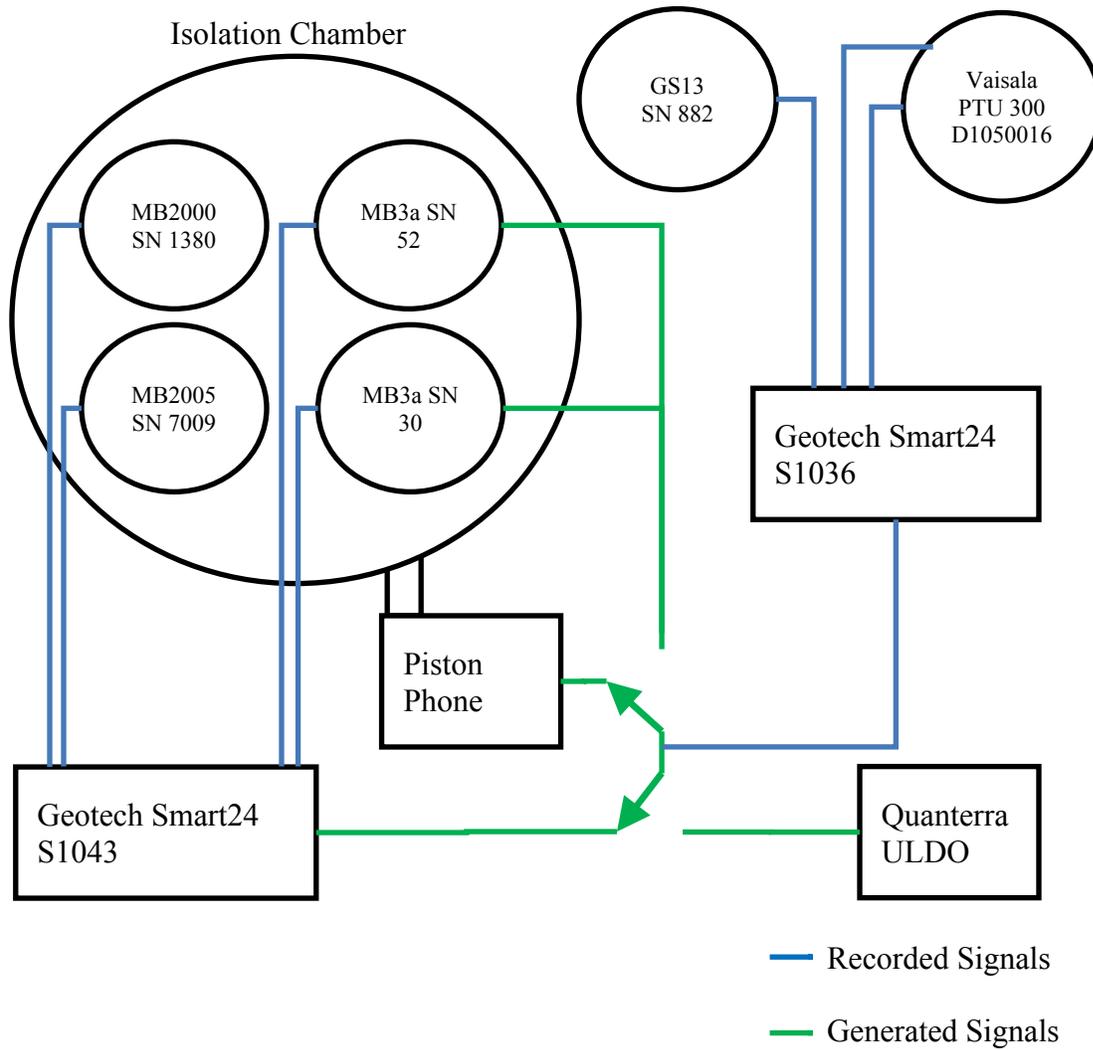


Figure 2 Test Configuration Diagram



Figure 3 Isolation Chamber, MB2000 and MB2005 References, MB3a Sensors

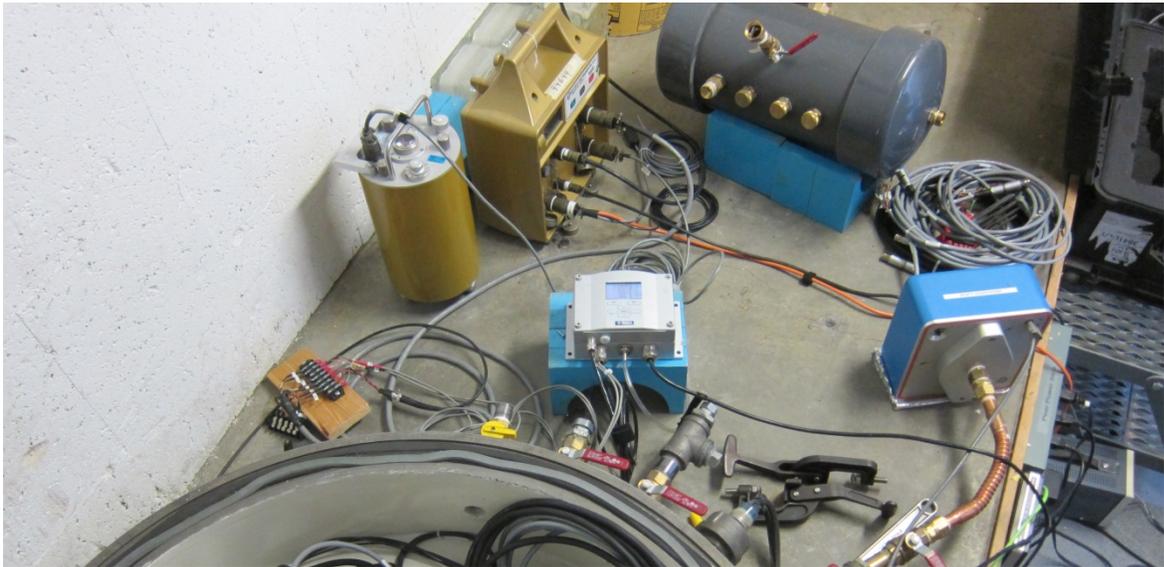


Figure 4 GS13 Seismometer, Vaisala Pressure & Temperature Reference, and Piston-Phone

2.5.1 Power

All of the sensors and digitizers within the testbed were powered off of an isolated 12 Volt battery bank that is kept charged with solar panels and a charge controller.

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 bitweight 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 bitweight 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 100 Hz rate data is used to fully capture the pass band of the MB3a sensor and the 20 Hz rate data is representative of the intended IMS use.

The digitizer bitweights 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 bitweights, shown in the digitizer configuration tables below, were used for all collected sensor data.

Table 2 Geotech Smart24 Digitizer S1036 Configuration

Channel Name	Bitweight	Description
c1p / c1s	0.40956 uV/count	GS13 Vertical Seismometer
c4p / c4s	3.2769 uV/count	Vaisala Ambient Pressure
c5p / c5s	3.26912 uV/count	Signal Generator Output
c6p / c6s	3.27587 uV/count	Vaisala Ambient Temperature

Table 3 Geotech Smart24 Digitizer S1043 Configuration

Channel Name	Bitweight	Description
c1p / c1s	3.26343 uV/count	MB2000 SN1380
c2p / c2s	3.24779 uV/count	MB2005 SN7009
c4p / c4s	3.25305 uV/count	MB3a SN52
c5p / c5s	3.25293 uV/count	MB3a SN30

2.5.3 Signal Generation

The test signals were generated either from the Geotech Smart24 S1043 calibrator output or from a Quanterra Ultra Low Distortion Oscillator (ULDO). Generally, the Smart24 was used to generate signals tests involving tones or white noise and the Quanterra ULDO was used to generate the high purity tones for the harmonic distortion tests and for the linearity 2-tone signals. The generated signals could then be fed into a piston-phonograph and converted into a varying pressure into the isolation chamber or directly into the MB3a calibration input. In all cases, the generated signals were synchronously recorded on channel 5 of the Geotech Smart24 S1036 digitizer.

2.5.4 Reference Sensors

Several reference sensors were used throughout the test.

An MB2000 SN 1380 and MB2005 SN 7009 were co-located within the isolation chamber to provide a reference measurement for the testing of the MB3a 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 transfer calibration was performed at the SNL FACT site to validate that the MB2000 sensitivity of 100 mV/Pa was consistent with the MB2005. In addition, after the testing of the MB3a's was performed, a static pressure calibration of both the MB2000 and MB2005 was performed at Sandia using a Keller portable calibrator which determined the MB2000 and MB2005 sensitivities to be correct to within 1%.

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 infrasound sensors under evaluation were provided by CEA. The infrasound sensors were stated to have an output sensitivity of 20 mV/Pa and were designed for a differential output of +/- 24 Volts. The nominal sensitivity was used in the processing and analysis of all sensor data. The sensitivity of the calibrator input was stated to be 6 Pa/V. The frequency passband is specified to be 0.01 to 28 Hz. The power input voltage range is 7 – 20 Volts DC, with reverse polarity protection.

CEA provided the necessary power and signal cables to connect to the MB3a sensor. SNL added connectors as needed to interface the MB3a sensors to the Smart24 testbed digitizer. SNL provided power to the MB3a's using the separate power connector rather than the signal cable. On the signal cable, the absolute pressure output, calibrator input, and calibrator relay were used. When performing calibrations of the MB3a with its internal calibrator, the calibration relay was connected to the same 12 Volt DC supply as was used to power the sensors.

2.5.6 Ambient Conditions

Testing of the MB3a 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.

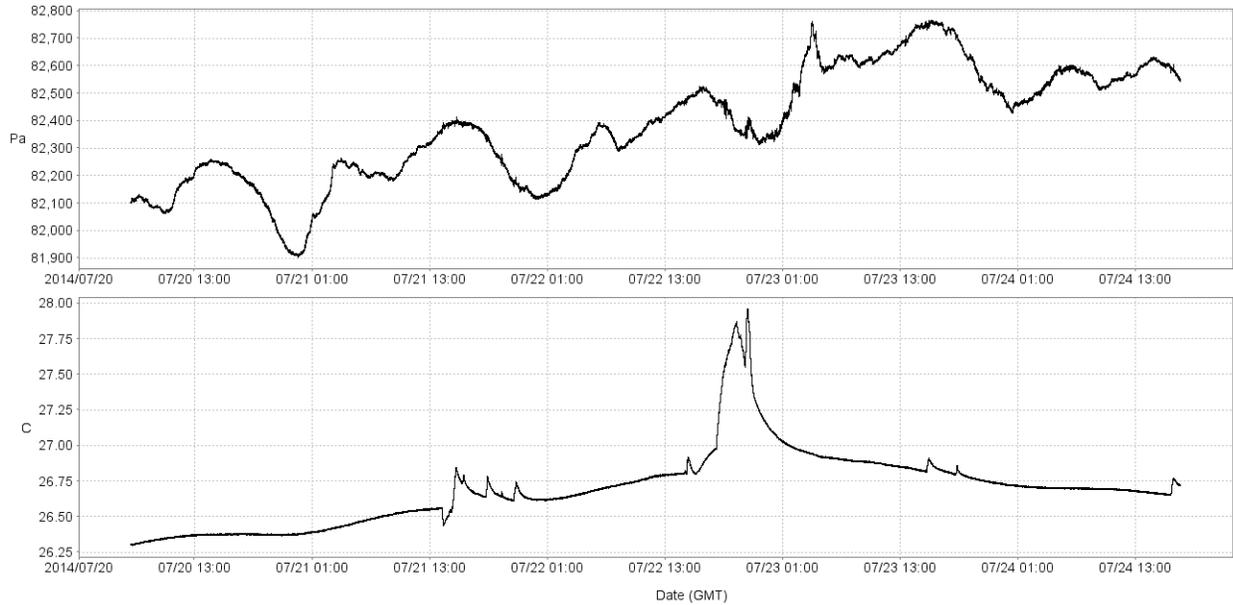


Figure 5 Ambient Pressure and Temperature

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 81,900 and 82,750 Pa during the days of testing.

The ambient temperature in the FACT bunker is very stable during the night with temperatures ranging between 26.5 and 27 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 7 – 20 V DC. The evaluation of the MB3a sensors was performed at a nominal voltage of 12 V DC powered by a battery. Measurements of voltage and current were made with two hand-held Fluke multi-meters.

Table 4 MB3a Power Consumption

Sensor	Power Supply Voltage	Current	Power Consumption
MB3a SN 30	13.18 V	9.24 mA	121.78 mW
MB3a SN 52	13.19 V	9.26 mA	122.14 mW

The observed power consumption of the MB3a was approximately 122 mW at 13.2 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, the digitizer channels recording the MB3a sensors were set to a 16x gain, with a bitweight of 0.2033 uV/count, so as to minimize the noise present on the input channel. A common 12 hour time window was used on both of the sensors. The vertical red bars define start and end of the time window used in the self-noise analysis.

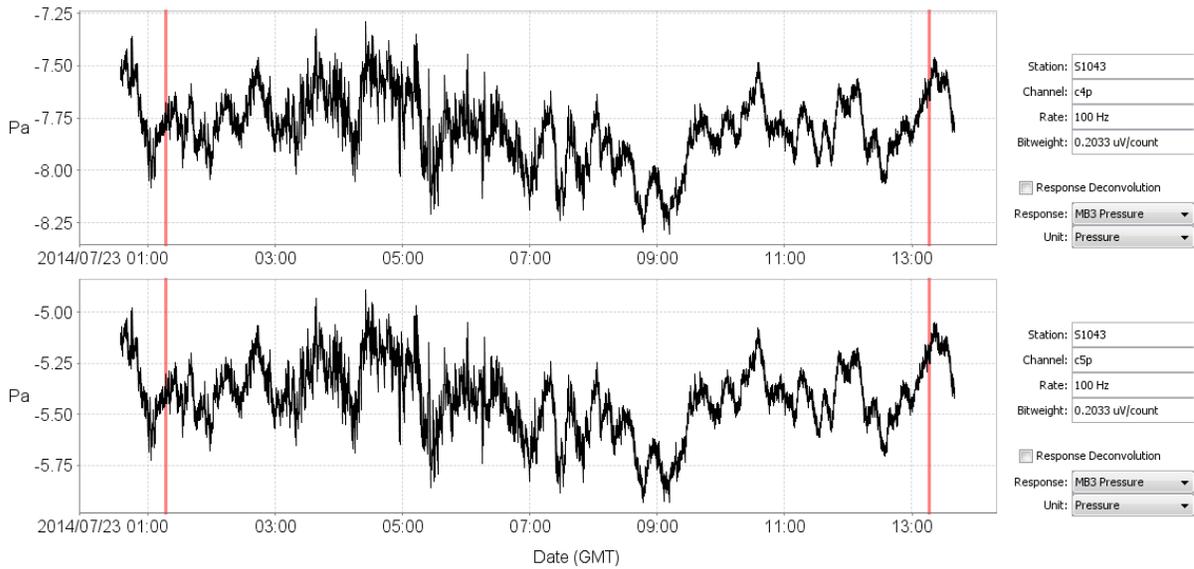


Figure 6 MB3a Isolation Time Series

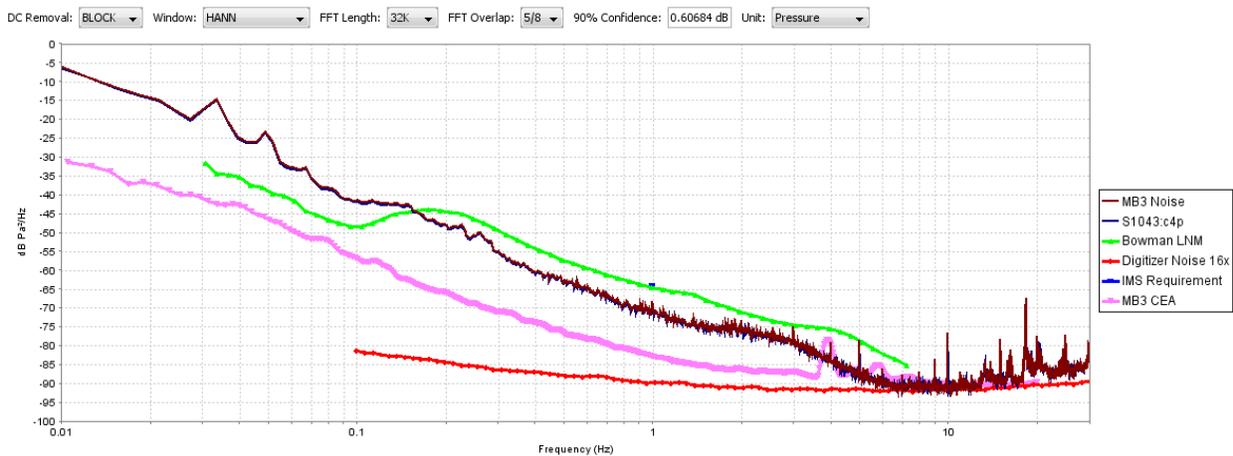


Figure 7 MB3a Isolation Power Spectra

Even with the presence of the isolation chamber to attenuate signals, there remains some coherent signal between the two MB3a sensors and the MB2000 reference sensor. Therefore, the 2-channel coherence technique was applied to the power spectra of the two MB3a sensors to compute their incoherent noise, using a distributed noise model that assumes that the noise is evenly distributed between the two sensors. The MB3a noise, the Bowman Low Noise Model (LNM), measured digitizer noise at a gain of 16x, the IMS noise requirement, and an MB3a noise model provided by CEA are shown on the plot below.

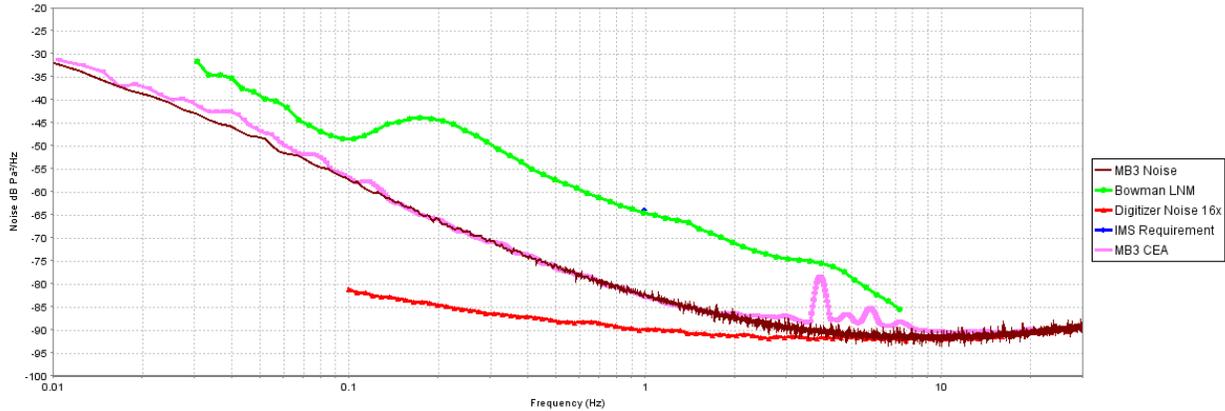


Figure 8 MB3a Isolation Incoherent Self-Noise

As may be seen, the evaluated MB3a self-noise is consistent with the noise model provided by CEA and is more than 36 dB below the noise level of 5 mPa/√Hz at 1 Hz, exceeding the IMS requirement of being at least 18 dB below the same noise level. The observed sensor noise is slightly lower than the CEA noise model due to lower digitizer noise and the coherent removal of signals common to both sensors.

In addition, the MB3a self-noise is entirely below the Bowman LNM across its defined frequency range of 0.03 to 7 Hz.

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 MB3's 24 V clip level at 1 Hz are:

Table 5 MB3a RMS Noise and Dynamic Range

	20 mHz - 4 Hz	10 mHz - 28 Hz
MB3a Noise	1.493 mPa rms	2.554 mPa rms
Dynamic Range	115.09 dB	110.43 dB

The estimated MB3a dynamic range of more than 115 dB exceeds the IMS requirement of 108 dB across the 0.02 – 4 Hz pass band. Across the entire pass band of the MB3, 0.01 – 28 Hz, the estimated dynamic range still exceeds 110 dB.

Note that for frequencies below 1.6 Hz, CEA specifications state that the MB3a has a dynamic range of 117 dB across 0.02 – 4 Hz. This estimate of dynamic range is computed from the ratio of the RMS of a full-scale square wave to the RMS noise present in the sensor self-noise. The difference in SNL’s and CEA’s definitions for dynamic range causes CEA’s dynamic range values to be approximately 3 dB higher. Therefore, SNL’s and CEA’s estimates of dynamic range are consistent with SNL’s estimate being approximately 1 dB higher than predicted due to the lower estimate of sensor self-noise.

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 and amplitudes 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 20 cycles of each tone were recorded.

Table 6 Piston-phone Tone Amplitudes

Amplitudes (Volts) into piston-phone	Approximate pressure (at 1 Hz) within the chamber
0.1 V	0.135 Pa
0.5 V	0.71 Pa
1 V	1.51 Pa
1.5 V	2.37 Pa
2 V	3.23 Pa
2.5 V	3.97 Pa
3 V	4.6 Pa

Table 7 Piston-phone Tone Frequencies

Frequencies
0.01 Hz
0.1 Hz
1 Hz
1.41 Hz
2 Hz
5 Hz
10 Hz

The sequences of tones were run twice: first during the day to ensure they were correct and a second time overnight when temperature variations, wind, and other man-made noise sources were minimal. The results from the two sequences are consistent. The overnight results are shown below.

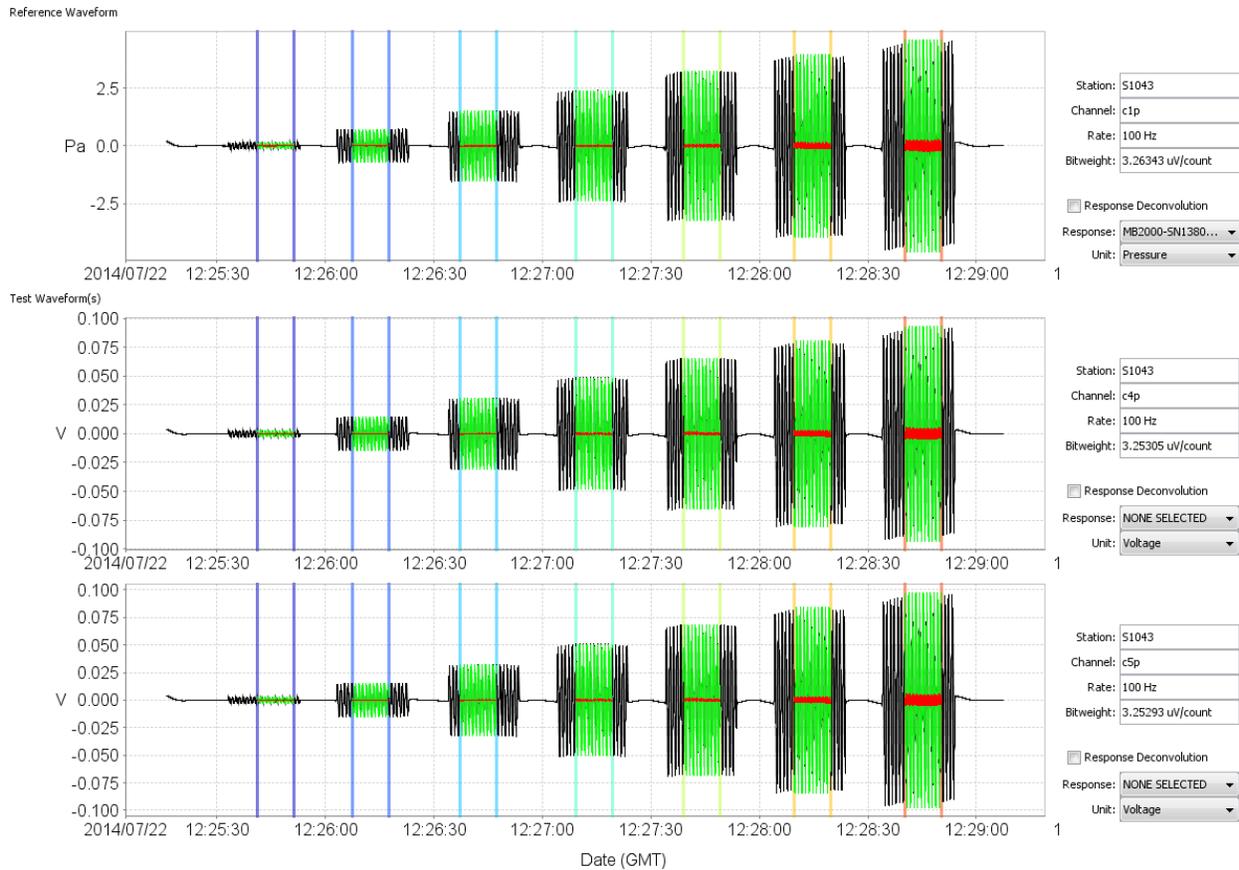


Figure 9 Piston-phone Tone Time Series for 1 Hz

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. Where needed, a post-processing filter was applied to the waveform data to remove frequency content outside of the frequency 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 8 Piston-phone Sensitivities vs Pressure and Frequency for MB3a SN30

Pressure (at 1 Hz)	0.13419 Pa	0.71099 Pa	1.50652 Pa	2.36909 Pa	3.22899 Pa	3.97288 Pa	4.60412 Pa
0.01 Hz	7.8583 mV/Pa*	15.04682 mV/Pa	15.1002 mV/Pa	15.06929 mV/Pa	15.07778 mV/Pa	15.08009 mV/Pa	15.08301 mV/Pa
0.1 Hz	21.23947 mV/Pa	21.23855 mV/Pa	21.22803 mV/Pa	21.23087 mV/Pa	21.22809 mV/Pa	21.2316 mV/Pa	21.23215 mV/Pa
1 Hz	21.24154 mV/Pa	21.19205 mV/Pa	21.20104 mV/Pa	21.19698 mV/Pa	21.18993 mV/Pa	21.19369 mV/Pa	21.19667 mV/Pa
1.41 Hz	21.19045 mV/Pa	21.16637 mV/Pa	21.15832 mV/Pa	21.15065 mV/Pa	21.1548 mV/Pa	21.15208 mV/Pa	21.15436 mV/Pa
2 Hz	21.05205 mV/Pa	21.10102 mV/Pa	21.09361 mV/Pa	21.09228 mV/Pa	21.09075 mV/Pa	21.09253 mV/Pa	21.09242 mV/Pa
5 Hz	20.84193 mV/Pa	20.64477 mV/Pa	20.67116 mV/Pa	20.65139 mV/Pa	20.66099 mV/Pa	20.65065 mV/Pa	20.65769 mV/Pa
10 Hz	19.17531 mV/Pa	19.411 mV/Pa	19.4066 mV/Pa	19.41745 mV/Pa	19.42019 mV/Pa	19.40925 mV/Pa	19.41398 mV/Pa

*The signal to noise ratio was very low on this tone which prevented an adequate sinusoid fit.

Table 9 Piston-phone Sensitivities vs Pressure and Frequency for MB3a SN52

Pressure (at 1 Hz)	0.13419 Pa	0.71099 Pa	1.50652 Pa	2.36909 Pa	3.22899 Pa	3.97288 Pa	4.60412 Pa
0.01 Hz	7.42117 mV/Pa*	14.55745 mV/Pa	14.58072 mV/Pa	14.57365 mV/Pa	14.57251 mV/Pa	14.57372 mV/Pa	14.5768 mV/Pa
0.1 Hz	20.44228 mV/Pa	20.44763 mV/Pa	20.44461 mV/Pa	20.4471 mV/Pa	20.44602 mV/Pa	20.44648 mV/Pa	20.44635 mV/Pa
1 Hz	20.33883 mV/Pa	20.29536 mV/Pa	20.30447 mV/Pa	20.30123 mV/Pa	20.29498 mV/Pa	20.2984 mV/Pa	20.30081 mV/Pa
1.41 Hz	20.27884 mV/Pa	20.24698 mV/Pa	20.24618 mV/Pa	20.23772 mV/Pa	20.24252 mV/Pa	20.23966 mV/Pa	20.24201 mV/Pa
2 Hz	20.12345 mV/Pa	20.17642 mV/Pa	20.16679 mV/Pa	20.16528 mV/Pa	20.16383 mV/Pa	20.16565 mV/Pa	20.16523 mV/Pa
5 Hz	19.91769 mV/Pa	19.71405 mV/Pa	19.73662 mV/Pa	19.71716 mV/Pa	19.72624 mV/Pa	19.71518 mV/Pa	19.72198 mV/Pa
10 Hz	18.37457 mV/Pa	18.58497 mV/Pa	18.57874 mV/Pa	18.5893 mV/Pa	18.59049 mV/Pa	18.57901 mV/Pa	18.58291 mV/Pa

*The signal to noise ratio was very low on this tone which prevented an adequate sinusoid fit.

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

Table 10 Piston-phone Average Sensitivities

	Average Sensitivity at 1 Hz	Difference from 20mV/Pa	Maximum difference from average at 1 Hz across 0.134 – 4.6 Pa	Maximum difference from average across 0.02 – 4 Hz
MB3a SN30	21.20 mV/Pa	6 % (0.51 dB)	0.19 % (0.016 dB)	0.71 % (0.061 dB)
MB3a SN52	20.30 mV/Pa	1.5 % (0.13 dB)	0.17 % (0.0145 dB)	0.89 % (0.077 dB)

The sensitivities of the MB3a SN30 and SN50 sensors were observed to be 21.20 mV/Pa and 20.3 mV/Pa at 1 Hz, respectively. These sensitivity values differed from the nominal sensitivity of 20 mV/Pa by 6% (0.51 dB) and 1.5% (0.13 dB), respectively. Both sensors were flat across the 0.134 to 4.6 Pa amplitude range to within +/- 0.198% (0.016 dB) and +/- 0.17% (0.0145 dB) respectively. A slight variation in sensitivity across frequency was observed, however this variation is consistent with the roll off present in the response corrections provided by CEA and are to be expected. Across the 0.02 – 4 Hz passband, the observed sensitivities differed from the average by +/- 0.71% (0.061 dB) and +/- 0.89% (0.077 dB), respectively.

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 was generated by the calibration output channel of a Smart24 testbed digitizer with amplitude of 1.0 Volt. This white noise signal was fed into a piston-phone infrasound source attached to the 330L infrasound test chamber for two hours.

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. 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 0.66 dB.

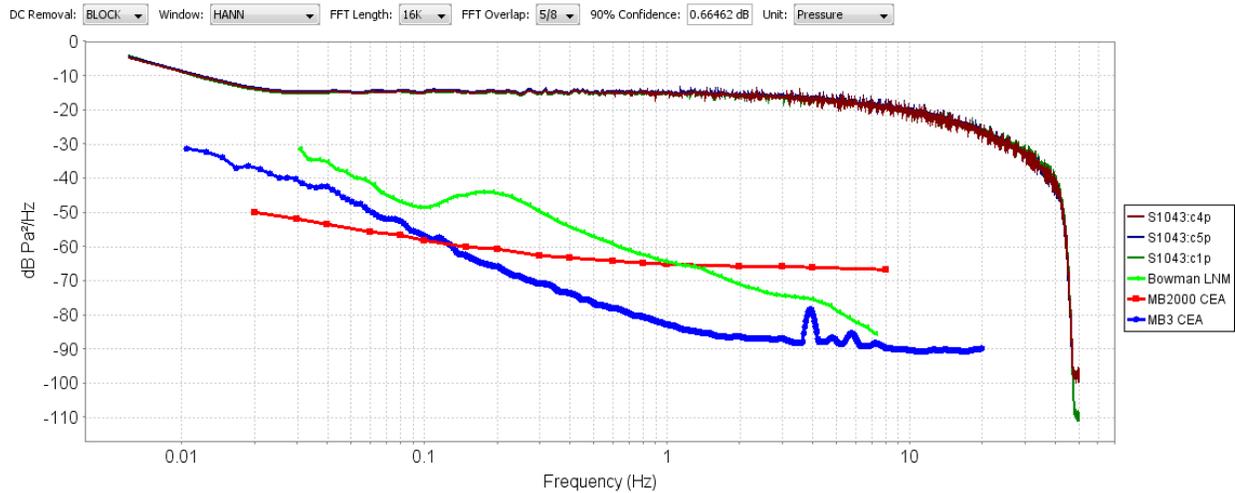


Figure 10 Piston-phone White Noise Power Spectra

The PSDs show good broadband agreement with the MB2000 reference sensor from 0.01 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 MB3a sensors under evaluation are plotted below.

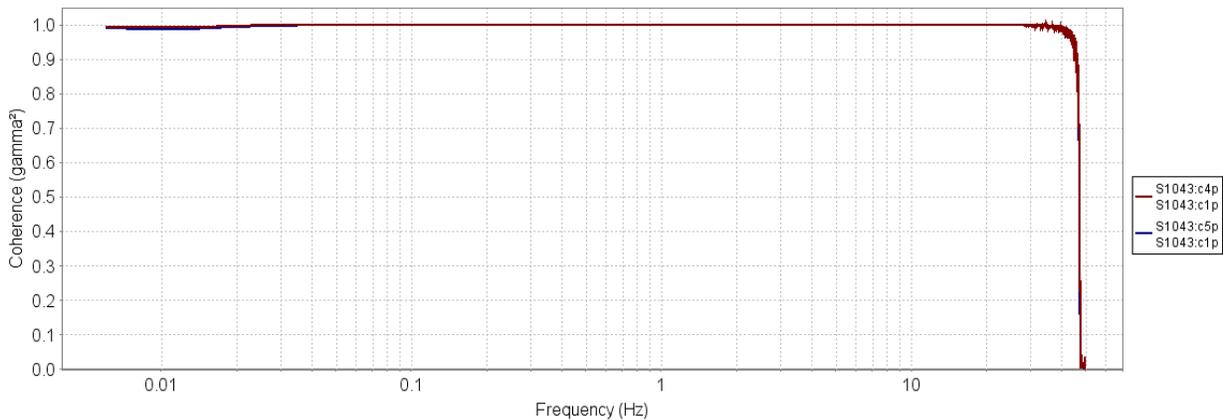


Figure 11 Piston-phone White Noise Coherence

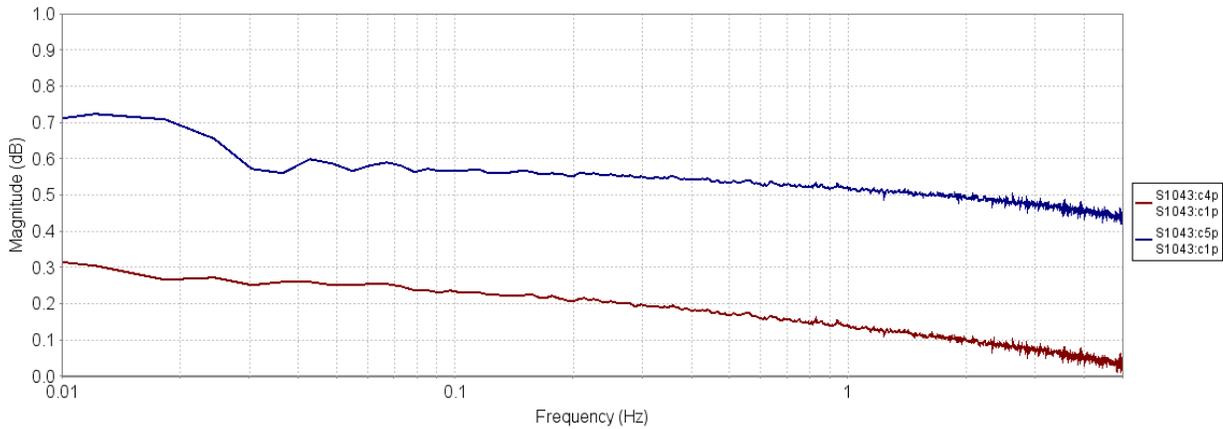


Figure 12 Piston-phone White Noise Relative Magnitude, 0.02 – 4 Hz

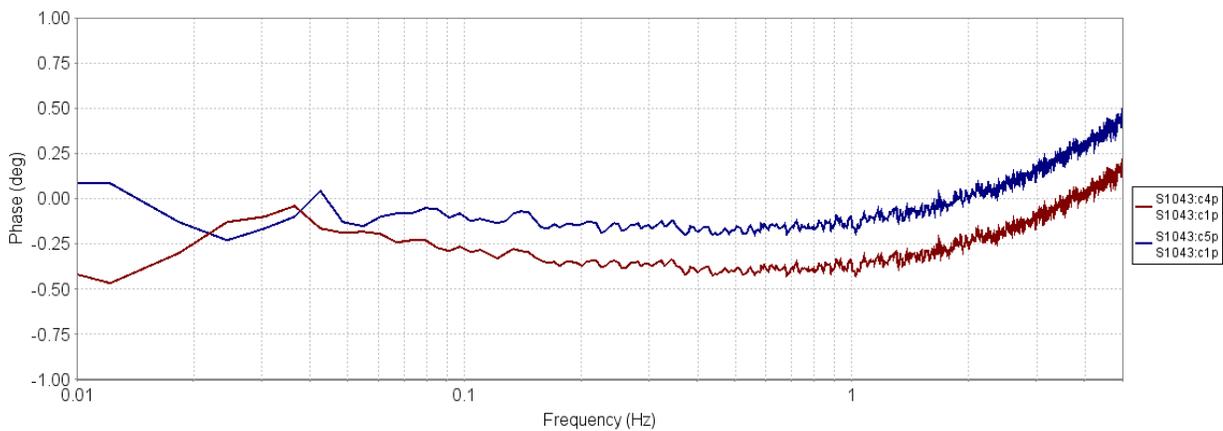


Figure 13 Piston-phone White Noise Relative Phase, 0.02 – 4 Hz

Here we can see that the variation in magnitude and phase between the outputs of the MB2000 reference and each of the MB3a sensors are described in the table below.

Table 11 Piston-phone White Noise Relative Magnitude and Phase, 0.02 – 4 Hz

	Magnitude, 0.02 – 4 Hz	Phase, 0.02 – 4 Hz
S1043:c4p (MB3a SN 52)	+0.25 dB / +0.05 dB	+0.1 deg / -0.25 deg
S1043:c5p (MB3a SN 30)	+0.7 dB / +0.45 dB	+0.3 deg / -0.25 deg

The theoretical response models for both the MB2000 and the MB3a have a 3 dB low frequency corner at 0.01 Hz and then flat out beyond 4 Hz. Given the agreement between the response corrected outputs, the evaluated MB3a sensors are consistent with their theoretical response model. Therefore, both the MB3a sensors appear to have a pass band that is flat to within 0.25 dB and 0.6 degrees over 0.02 to 4 Hz.

There appears to be a fairly consistent 0.4 dB difference in the relative magnitude responses of the two MB3a sensors when measuring a coherent white noise signal.

Examining the 100 Hz data to evaluate the full pass band of the MB3a sensors, the magnitude and phase response relative to the MB2000 reference are shown in the plots below:

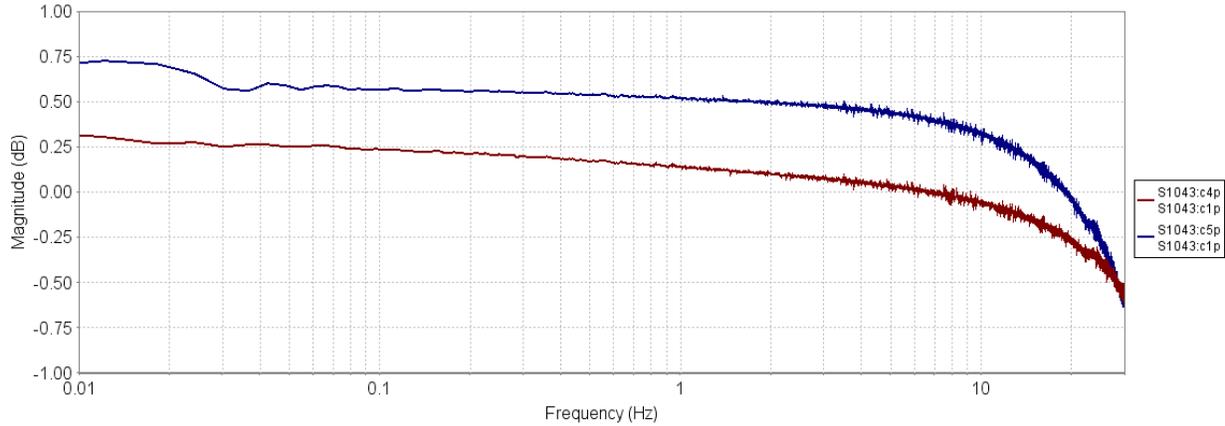


Figure 14 Piston-phone White Noise Relative Magnitude, 0.01 – 28 Hz

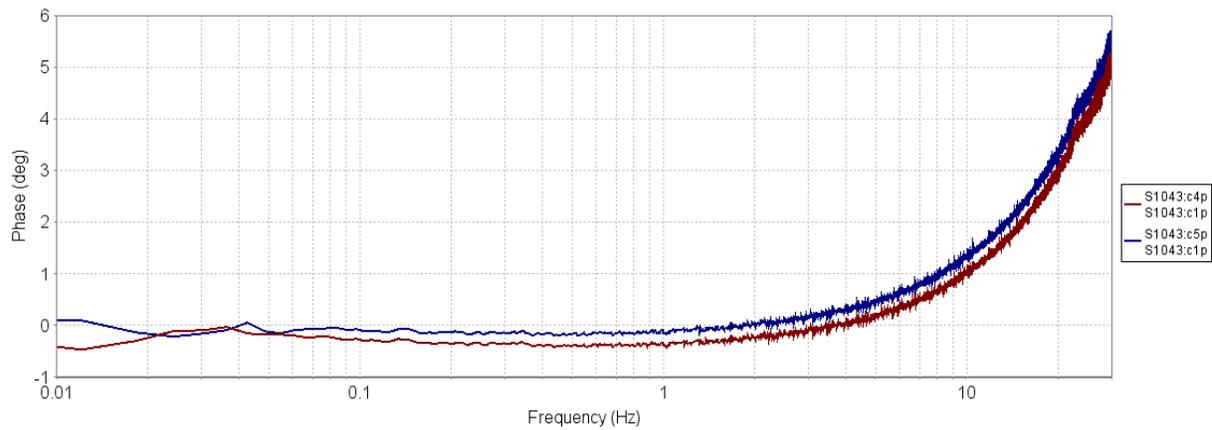


Figure 15 Piston-phone White Noise Relative Phase, 0.01 – 28 Hz

Here we can see that the variation in magnitude and phase between the outputs of the MB2000 reference and each of the MB3a sensors are described in the table below.

Table 12 Piston-phone White Noise Relative Magnitude and Phase, 0.01 – 28 Hz

	Magnitude, 0.01 – 28 Hz	Phase, 0.01 – 28 Hz
S1043:c4p (MB3a SN 52)	+0.3 dB / -0.5 dB	-0.5 deg / +4.5 deg
S1043:c5p (MB3a SN 30)	+0.75 dB / -0.5 dB	+0 deg / +4.8 deg

The relative magnitude and phase are fairly flat across their 0.01 to 28 Hz pass band to within 0.8 dB and 5 degrees for SN 52 and 1.25 dB and 4.8 degrees for SN 30.

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 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 0.66 dB.

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

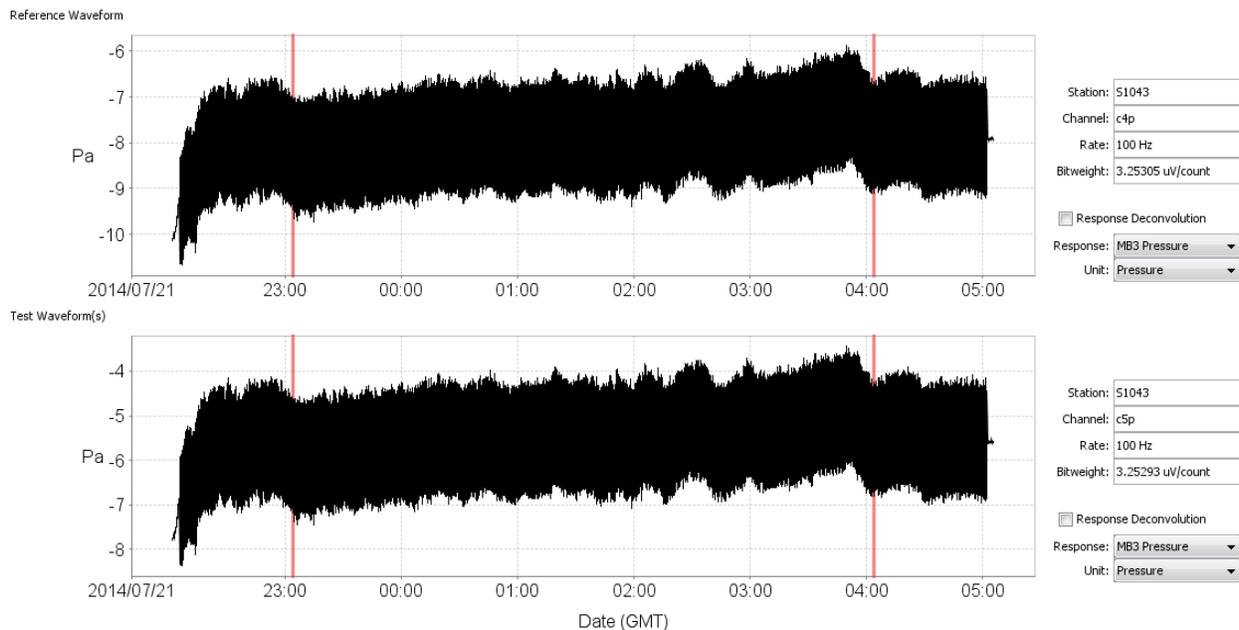


Figure 16 MB3a Dynamic Noise Time Series

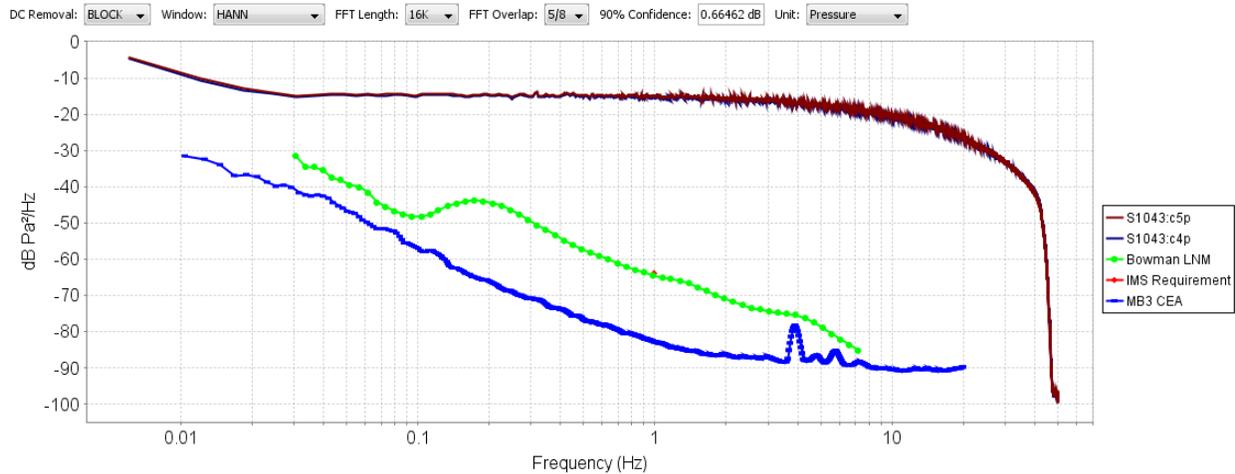


Figure 17 MB3a Dynamic Noise Power Spectra

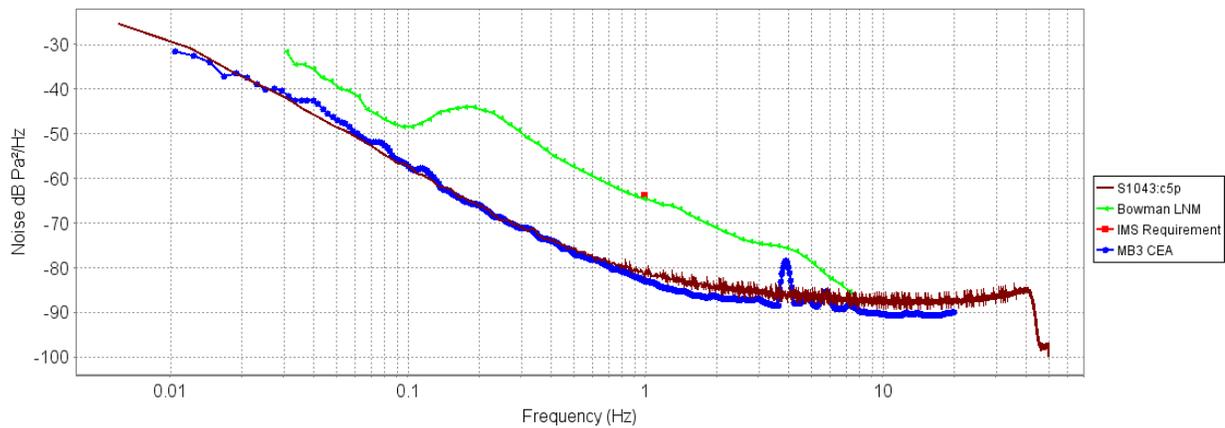


Figure 18 MB3a Dynamic Noise Incoherent Noise

We observe that the MB3a self-noise, represented by the incoherent noise, is consistent with the MB3a noise model from CEA and the isolation self-noise (3.2 Isolation Noise). This is significant as the white noise input signal is as much as 70 dB above the self-noise at frequencies above 1 Hz.

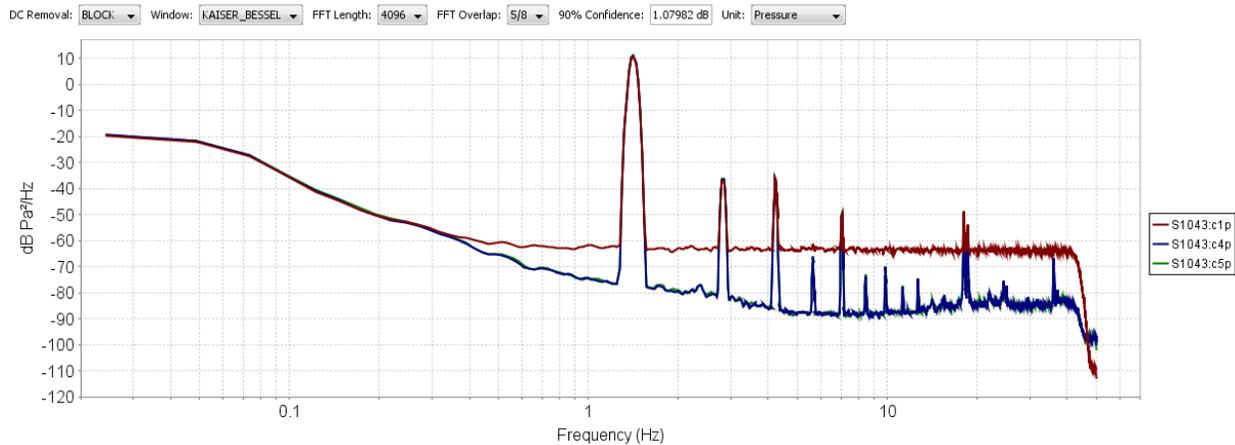
Even under dynamic conditions, the MB3a self-noise is more than 35 dB below the minimum noise level of $5 \text{ mPa}/\sqrt{\text{Hz}}$ at 1 Hz, exceeding the IMS requirement of at least 18 dB below.

3.7 Harmonic Distortion

Test description: The purpose of the harmonic distortion test is to verify the linearity of the sensor. A Quanterra ultra-low-distortion oscillator is used to generate a very pure sinusoid with a frequency of 1.41 Hz and amplitude of 2 V peak for approximately 20 minutes. The sinusoidal 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 power spectra of the time series was collected and analyzed to identify the fundamental frequency and all harmonics present (Merchant, 2011).



Waveform	Peak Count	Peak Frequency	Peak RMS	Secondary RMS	THD
S1043:c1p	7	1.41097 Hz	0.86255 Pa rms	3.72135 mPa rms	-43.89408 dB
S1043:c4p	9	1.41097 Hz	0.8759 Pa rms	3.75269 mPa rms	-44.25617 dB
S1043:c5p	9	1.41097 Hz	0.91477 Pa rms	3.92274 mPa rms	-44.21764 dB

The limiting factor in this test is that the piston-phone used in the testbed has a known limitation to its linearity of approximately -44 dB. The result of this test is that all of the sensors (MB2000 reference and MB3s) perform consistently with their known specifications and that none of them have any observed harmonic distortion greater than that of the piston-phone.

3.8 2-Tone

Test description: The purpose of the 2-Tone test is to verify the linearity of the sensor. A Quanterra ultra-low-distortion oscillator is used to generate a signal containing two tones. The first tone is a large amplitude (2 Pa), low frequency (0.01 Hz) sinusoid. The second tone is a smaller amplitude (0.5 Pa), higher frequency (1.23 Hz) sinusoid. The sinusoidal signal was fed into a piston-phone infrasound source attached to the 330L infrasound test chamber.

A sequence of 10 time windows for sine fits, each capturing 5 cycles of the 1.23 Hz tone, were then assigned across a half period of the low frequency sinusoid, as shown in the figure below.

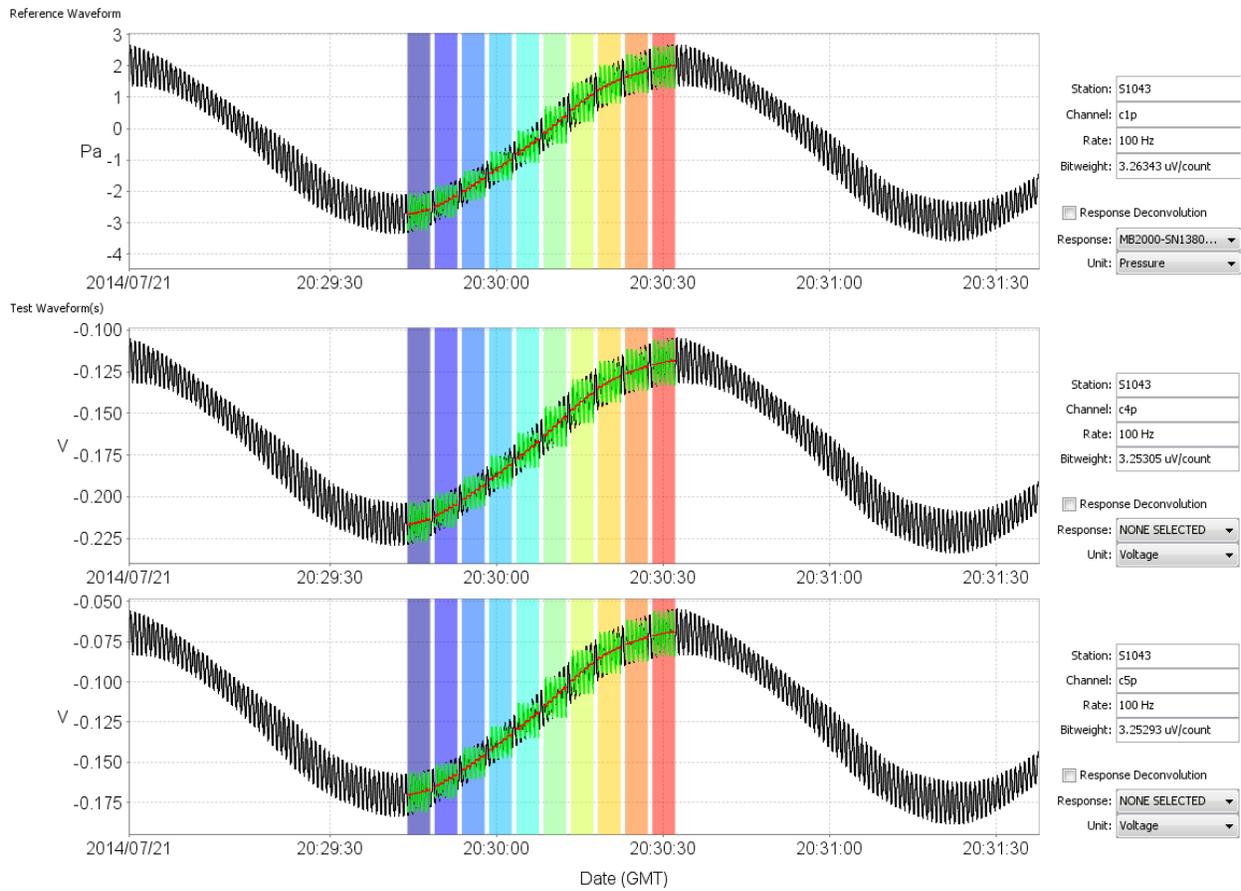


Figure 19 2-Tone Time Series

The time series were then filtered using a highpass butterworth filter with a cutoff frequency of 50 mHz. This filter will serve to remove the low frequency signal from the time series.

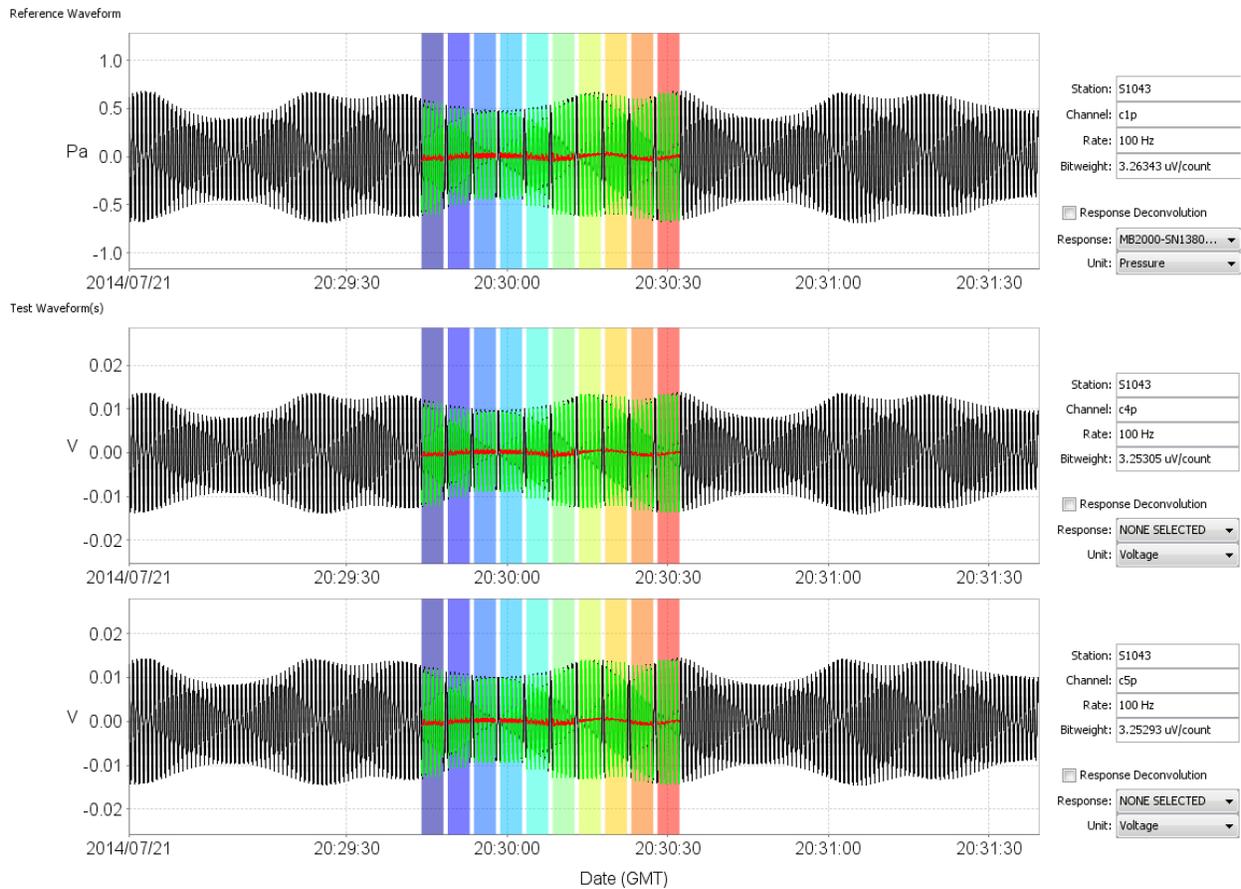


Figure 20 2-Tone Filtered Time Series

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. The observed variation in amplitude seen in the signal above is due to effects in the piston-phone source since they are observed across all of the sensors. The analysis of the amplitudes for the sensors under test is made relative to what was observed on the reference sensor, therefore any effects of the piston-phone should cancel out.

The linearity of the MB3a’s may be determined by examining the estimated sensitivity for variations. If the MB3a is perfectly linear across the amplitude range of the input tone, then there should be no variation, to within measurement error, of the sensitivities.

Table 13 2-Tone Sensitivities

	1	2	3	4	5	6	7	8	9	10
S1043:c4p (MB3a SN 52)	20.32852 mV/Pa	20.34695 mV/Pa	20.3399 mV/Pa	20.3398 mV/Pa	20.35041 mV/Pa	20.32848 mV/Pa	20.32724 mV/Pa	20.32864 mV/Pa	20.33793 mV/Pa	20.34684 mV/Pa
S1043:c5p (MB3a SN 30)	21.21366 mV/Pa	21.23632 mV/Pa	21.23258 mV/Pa	21.23471 mV/Pa	21.24393 mV/Pa	21.21334 mV/Pa	21.20992 mV/Pa	21.21609 mV/Pa	21.22262 mV/Pa	21.23134 mV/Pa

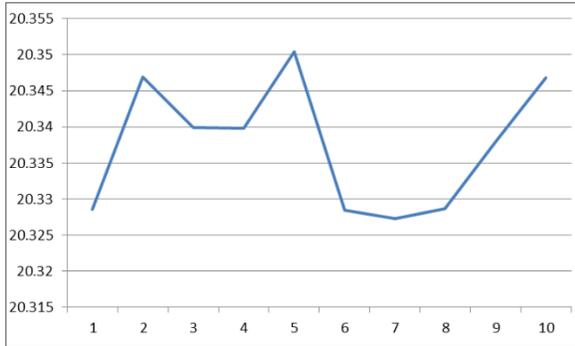


Figure 21 2-Tone Sensitivity MB3a SN52

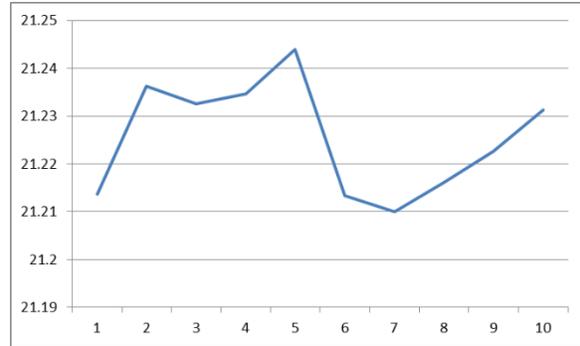


Figure 22 2-Tone Sensitivity MB3a SN30

MB3a SN52 was observed to have a mean sensitivity across the 2-Tone test of 20.3375 mV/Pa with a variation of +/- 0.0129 mV/Pa.

MB3a SN30 was observed to have a mean sensitivity across the 2-Tone test of 21.2255 mV/Pa with a variation of +/- 0.0185 mV/Pa.

The observed sensitivity variation in both sensors was less than 0.1%, which is below our measurement error. Therefore, using the piston-phone, the two MB3a's appear to be linear across a +/- 3 Pa range of amplitudes.

3.9 Calibrator Frequency Amplitude Response Verification

Test description: The purpose of the calibrator infrasound sensor frequency/amplitude response verification test is to determine or verify the infrasound sensor amplitude response at multiple frequencies using the sensors internal calibrator.

A sequence of tones covering the combination of frequencies and amplitudes below were generated by a Smart24 testbed digitizer. The tones were fed into both of the MB3's calibrator inputs and simultaneously recorded on a second Smart24 testbed digitizer. The MB3a sensors were enclosed within the 330 L isolation chamber with their inlets open to help isolate them from ambient pressure signals. Approximately 20 cycles of each tone were recorded.

Note that the MB3a calibrator input is expecting a single-sided input signal. The Smart24 signal generator outputs a differential signal. To compensate, only the positive leg and the ground line were connected to the MB3a calibrator input.

The MB3a calibrator enable relay was connected to the 12 V DC power supply to enable the calibrator.

Table 14 Calibrator Tone Amplitudes

Amplitudes (Volts) into MB3a calibrator	Equivalent Pressure (using 6 Pa/V calibrator sensitivity)
0.05 V	0.3 Pa
0.25 V	1.5 Pa
0.5 V	3 Pa
0.75 V	4.5 Pa
1 V	6 Pa
1.25 V	7.5 Pa
1.5 V	9 Pa

Table 15 Calibrator Tone Frequencies

Frequencies
0.01 Hz
0.1 Hz
1 Hz
1.41 Hz
2 Hz
5 Hz
10 Hz

The sequences of tones were run twice: first during the day to ensure they were correct and a second time overnight when temperature variations, wind, and other man-made noise sources are minimal. The results from the two sequences are consistent. The overnight results are shown below.

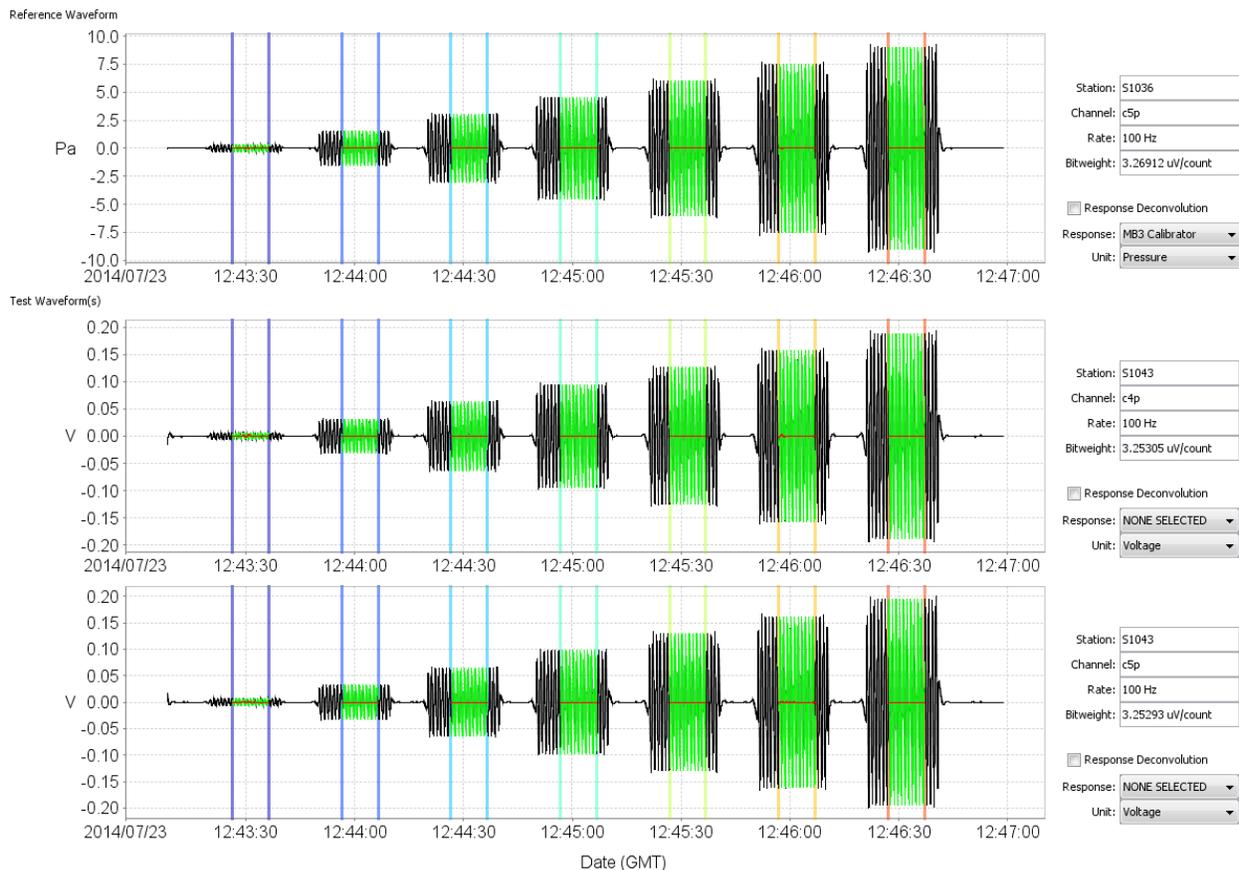


Figure 23 Calibrator Time Series Tones for 1 Hz

The pressure measurement for each of the tones was observed on the recording of the signal being inputted into the MB3a calibrator. The MB3a calibrator sensitivity of 6 Pa/V provided by CEA was used to convert the calibrator input voltage into a presumed reference pressure. 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. Where appropriate, a post-processing filter was applied to the waveform data to remove frequency content outside of the frequency of the tone so as to improve the performance of the sine fit algorithm. 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 16 Calibrator Sensitivities vs Pressure and Frequency for MB3a SN30

Pressure (at 1 Hz)	0.30 Pa	1.50 Pa	3.00 Pa	4.51 Pa	6.02 Pa	7.52 Pa	9.02 Pa
0.01 Hz	15.5862 mV/Pa	15.40524 mV/Pa	15.50763 mV/Pa	15.48722 mV/Pa	15.44926 mV/Pa	15.49004 mV/Pa	15.47189 mV/Pa
0.1 Hz	21.49794 mV/Pa	21.5518 mV/Pa	21.56603 mV/Pa	21.56164 mV/Pa	21.5762 mV/Pa	21.56974 mV/Pa	21.56492 mV/Pa
1 Hz	21.43874 mV/Pa	21.49767 mV/Pa	21.49851 mV/Pa	21.49795 mV/Pa	21.49903 mV/Pa	21.48118 mV/Pa	21.49951 mV/Pa
1.41 Hz	21.36475 mV/Pa	21.45626 mV/Pa	21.45903 mV/Pa	21.46923 mV/Pa	21.45809 mV/Pa	21.45831 mV/Pa	21.45304 mV/Pa
2 Hz	21.37362 mV/Pa	21.38418 mV/Pa	21.38802 mV/Pa	21.39907 mV/Pa	21.40368 mV/Pa	21.40016 mV/Pa	21.40822 mV/Pa
5 Hz	21.02121 mV/Pa	21.02448 mV/Pa	21.02358 mV/Pa	21.02237 mV/Pa	21.02514 mV/Pa	21.02486 mV/Pa	21.02486 mV/Pa
10 Hz	19.97823 mV/Pa	19.97998 mV/Pa	19.9806 mV/Pa	19.98147 mV/Pa	19.98033 mV/Pa	19.98059 mV/Pa	19.98272 mV/Pa

Table 17 Calibrator Sensitivities vs Pressure and Frequency for MB3a SN52

Pressure (at 1 Hz)	0.30 Pa	1.50 Pa	3.00 Pa	4.51 Pa	6.02 Pa	7.52 Pa	9.02 Pa
0.01 Hz	15.13938 mV/Pa	15.16425 mV/Pa	15.20549 mV/Pa	15.16323 mV/Pa	15.15731 mV/Pa	15.18525 mV/Pa	15.16079 mV/Pa
0.1 Hz	20.88575 mV/Pa	21.02558 mV/Pa	21.04778 mV/Pa	21.04683 mV/Pa	21.06608 mV/Pa	21.0594 mV/Pa	21.05405 mV/Pa
1 Hz	20.8105 mV/Pa	20.88594 mV/Pa	20.88523 mV/Pa	20.88503 mV/Pa	20.8862 mV/Pa	20.85045 mV/Pa	20.88764 mV/Pa
1.41 Hz	20.61785 mV/Pa	20.82455 mV/Pa	20.82969 mV/Pa	20.85324 mV/Pa	20.8293 mV/Pa	20.83007 mV/Pa	20.82161 mV/Pa
2 Hz	20.74558 mV/Pa	20.71914 mV/Pa	20.7378 mV/Pa	20.75443 mV/Pa	20.75788 mV/Pa	20.75297 mV/Pa	20.76955 mV/Pa
5 Hz	20.34665 mV/Pa	20.34105 mV/Pa	20.3392 mV/Pa	20.34002 mV/Pa	20.34122 mV/Pa	20.34167 mV/Pa	20.34211 mV/Pa
10 Hz	19.27285 mV/Pa	19.28587 mV/Pa	19.28916 mV/Pa	19.29015 mV/Pa	19.2895 mV/Pa	19.29054 mV/Pa	19.29244 mV/Pa

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

Table 18 Calibrator Average Sensitivities

	Average Sensitivity at 1 Hz	Difference from 20mV/Pa	Maximum difference from average at 1 Hz across 0.3 – 9 Pa	Maximum difference from average across 0.02 – 4 Hz
MB3a SN30	21.49 mV/Pa	7.45 % (0.62 dB)	0.23 % (0.02 dB)	0.57 % (0.049 dB)
MB3a SN52	20.87 mV/Pa	4.35 % (0.37 dB)	0.29 % (0.025 dB)	1.21 % (0.104 dB)

The sensitivities of the MB3a SN30 and SN50 sensors were observed to be 21.49 mV/Pa and 20.87 mV/Pa at 1 Hz, respectively. These sensitivity values differed from the nominal sensitivity of 20 mV/Pa by 7.45% (0.62 dB) and 4.35% (0.37 dB), respectively. Both sensors were flat across the 0.3 to 9 Pa amplitude range to within +/- 0.23% (0.02 dB) and +/- 0.29% (0.025 dB), respectively. A slight variation in sensitivity across frequency was observed, however this variation is consistent with the roll off present in the response corrections provided by CEA and are to be expected. Across the 0.02 – 4 Hz passband, the observed sensitivities differed from the average by +/- 0.57% (0.049 dB) and +/- 1.21% (0.104 dB), respectively.

3.10 Calibrator Frequency Amplitude Phase Verification

Test description: The purpose of the infrasound sensor calibrator frequency/amplitude/phase response verification test is to determine or verify the infrasound sensor frequency, amplitude, phase response at all frequencies using the sensors internal calibrator.

A band-width limited white noise signal was generated by a Smart24 testbed digitizer with amplitude of 1.0 Volts. This white noise signal was fed into both of the MB3a's calibrator inputs and simultaneously recorded on a second Smart24 testbed digitizer. The MB3a sensors were enclosed within the 300 L isolation chamber with their inlets open to help isolate them from ambient pressure signals. This test was run over night, and the data were collected and reviewed prior to processing.

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 Holcomb (1989) under the lumped noise model assumption, attributing all incoherent noise to the infrasound sensor. 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 0.66 dB.

Note that the MB3a calibrator input is expecting a single-sided input signal. The Smart24 signal generator outputs a differential signal. To compensate, only the positive line and the ground line were connected to the MB3a calibrator input.

The MB3a calibrator enable relay was connected to the 12 V DC power supply to enable the calibrator.

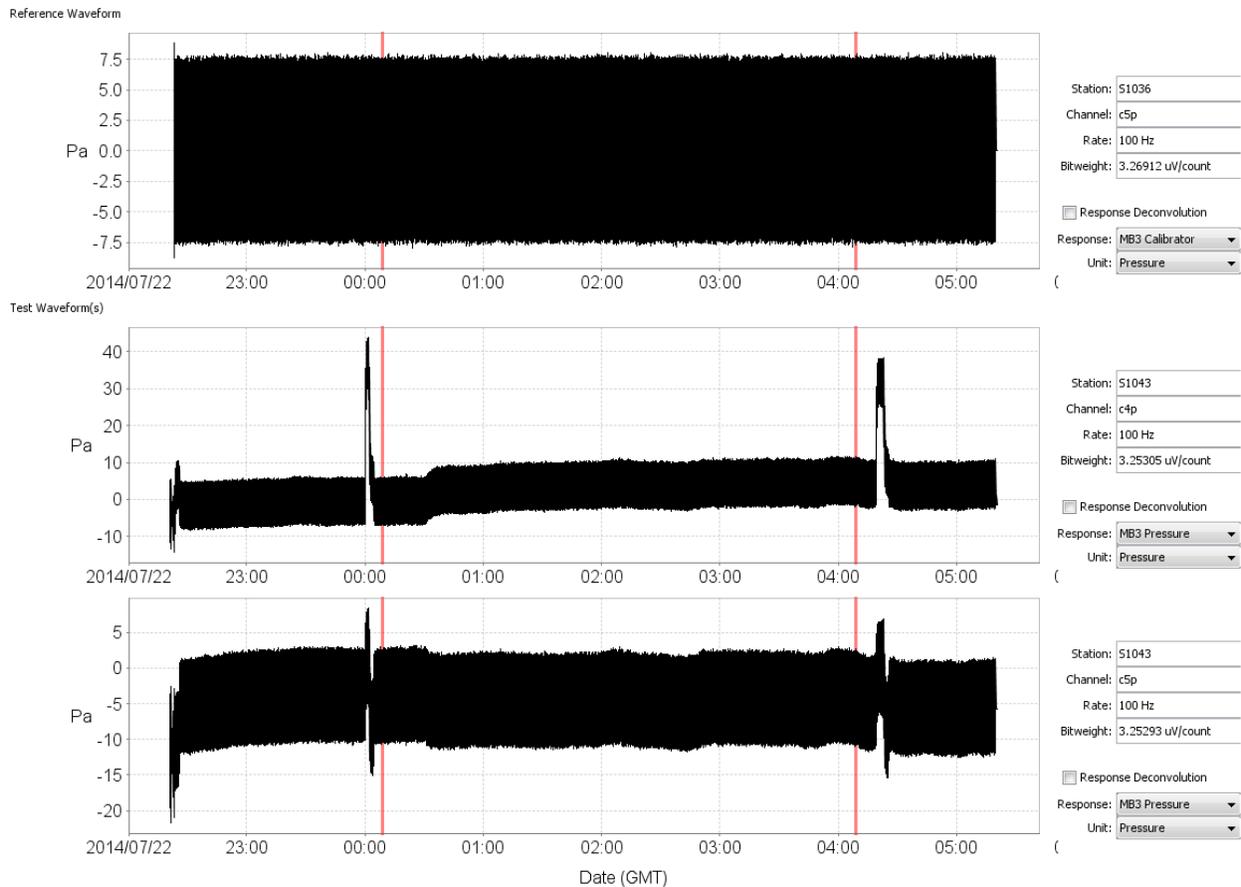


Figure 24 Calibrator White Noise Time Series

The MB3a does have a resonant mode in its mechanics at a frequency somewhere above its high frequency corner of 28 Hz. If there is significant input energy into the sensor at this frequency, it is possible for the mechanics to begin to resonate. It is believed that this occurred twice in the time series above in which there was a significant shift in the DC offset of the signal.

It should be noted that in case of acoustic or seismic signals with sufficiently high amplitude and high frequencies above the sensor pass band, some saturation effects may be observed, as described in the clipping level section of the datasheet. Similarly, any input calibration signals may have to be controlled to avoid this effect, especially using a broad band signal, such as white noise.

The power spectra of the output of the two MB3a sensors and the externally recorded input calibration signal (using the 6 Pa/V sensitivity of the calibration coil) are shown below.

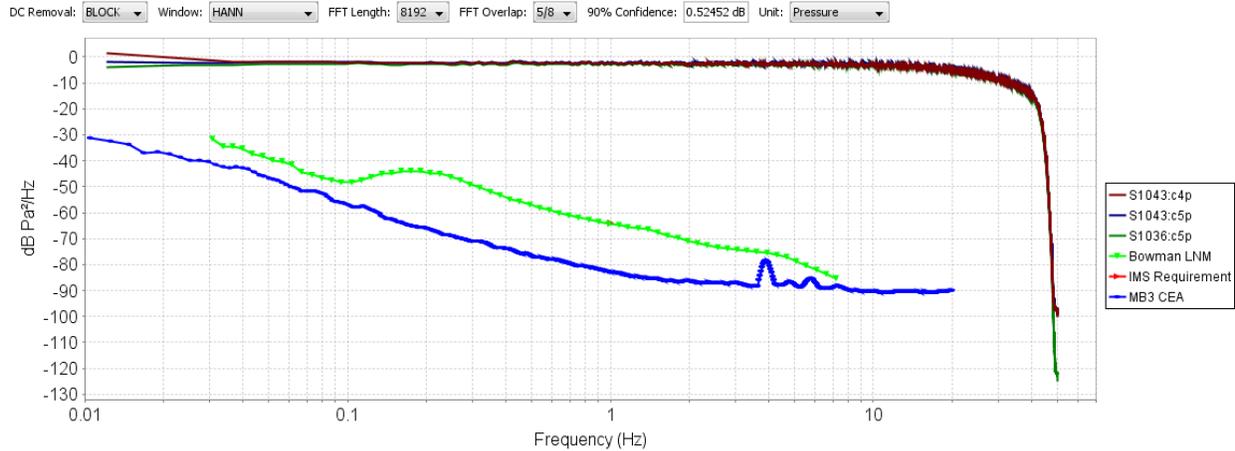


Figure 25 Calibrator White Noise Power Spectra

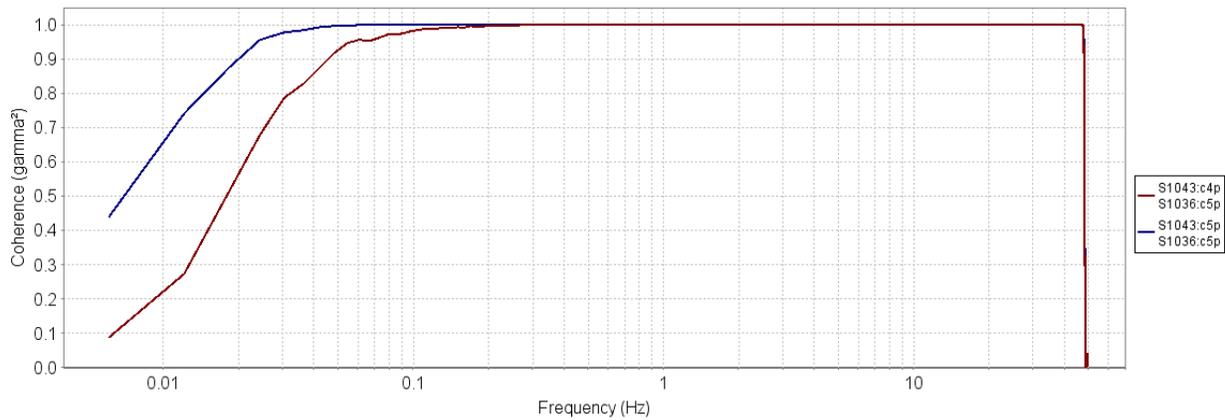


Figure 26 Calibrator White Noise Coherence

We see in the plot of the coherence between the calibrator input signal and the MB3a sensor outputs that the coherence is high at frequencies above 0.04 and 0.1 Hz. Coherence below 0.04 and 0.1 Hz, respectively, begins to drop off due to increasing amounts of self-noise present in the calibration coil. We will limit our observations below to the frequencies that have high coherence.

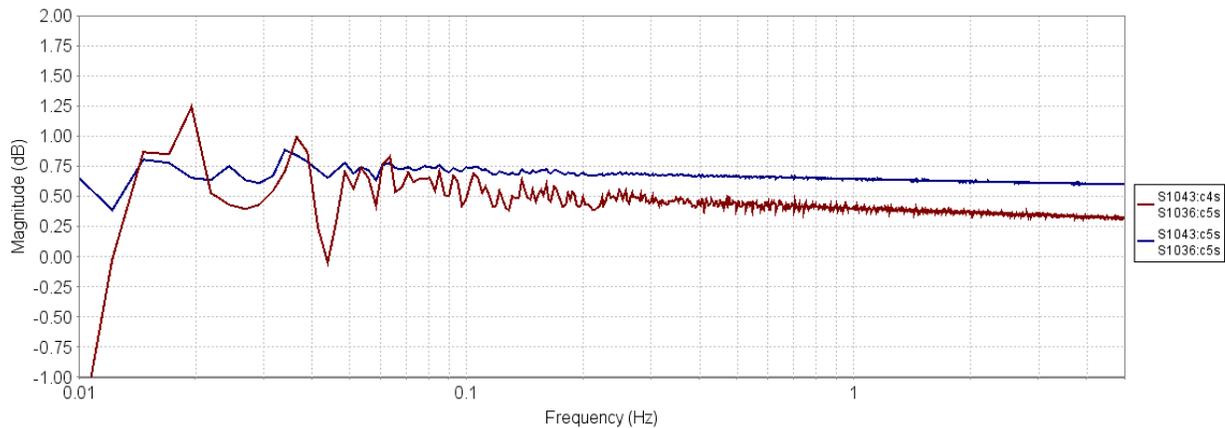


Figure 27 Calibrator White Noise Relative Magnitude, 0.02 – 4 Hz

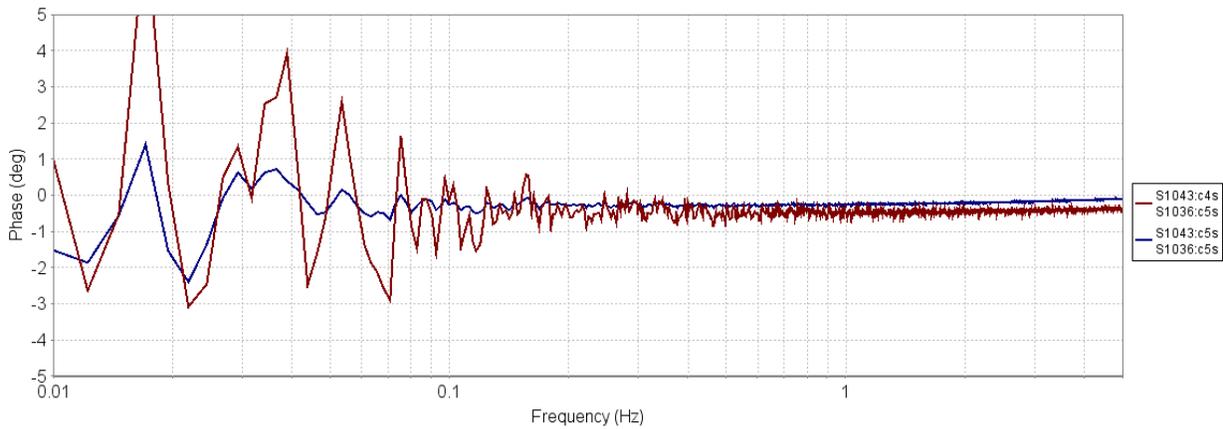


Figure 28 Calibrator White Noise Relative Phase, 0.02 – 4 Hz

Here we can see that the variation in magnitude and phase between calibrator input signal and each of the MB3a sensors are described in the table below.

Table 19 Calibrator White Noise Relative Magnitude and Phase, 0.02 – 4 Hz

	Magnitude, 0.02 – 4 Hz	Phase, 0.02 – 4 Hz
S1043:c4s (MB3a SN 52)	+0.75 dB / +0.3 dB	+1 deg / -1 deg
S1043:c5s (MB3a SN 30)	+0.75 dB / +0.6 dB	+0 deg / -0.5 deg

Note that for MB3a SN52 and SN30, we were unable to comment on the relative magnitude and phase response below 0.1 and 0.04 Hz, respectively.

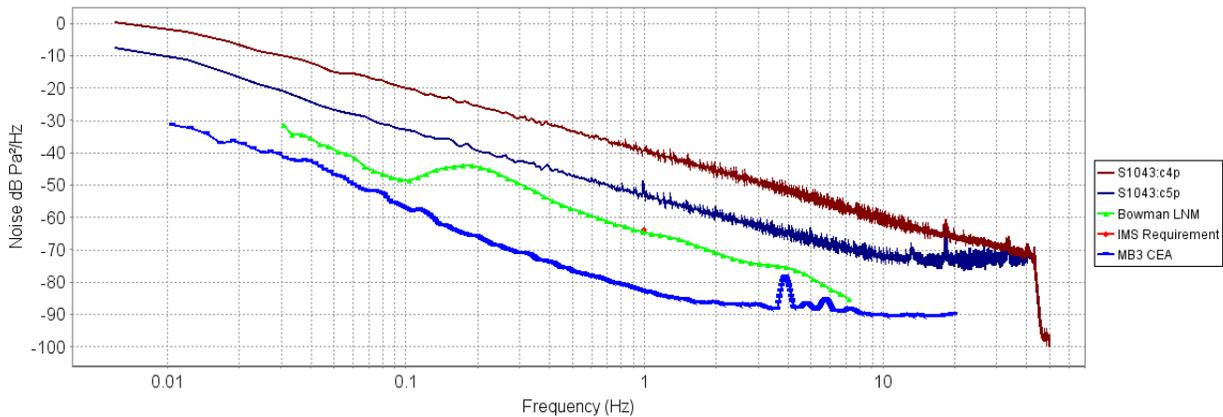


Figure 29 Calibrator Incoherent Noise

The calibration coils were observed to have significantly more noise than the sensing coils, shown in the plots of incoherent noise above. There are no specifications or requirements for noise in the calibrator. However, the observed levels are important to be aware of so that signal amplitude levels adequately above the calibrator noise may be selected.

Examining the 100 Hz data to evaluate the full pass band of the MB3a sensors, the magnitude and phase responses relative to the calibrator input signal are shown in the plots below:

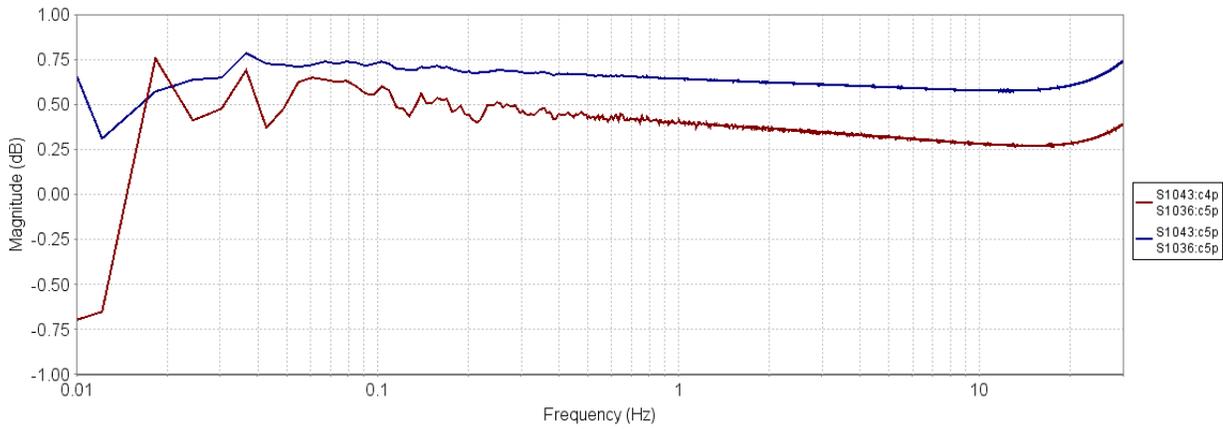


Figure 30 Calibrator White Noise Relative Magnitude, 0.01 – 28 Hz

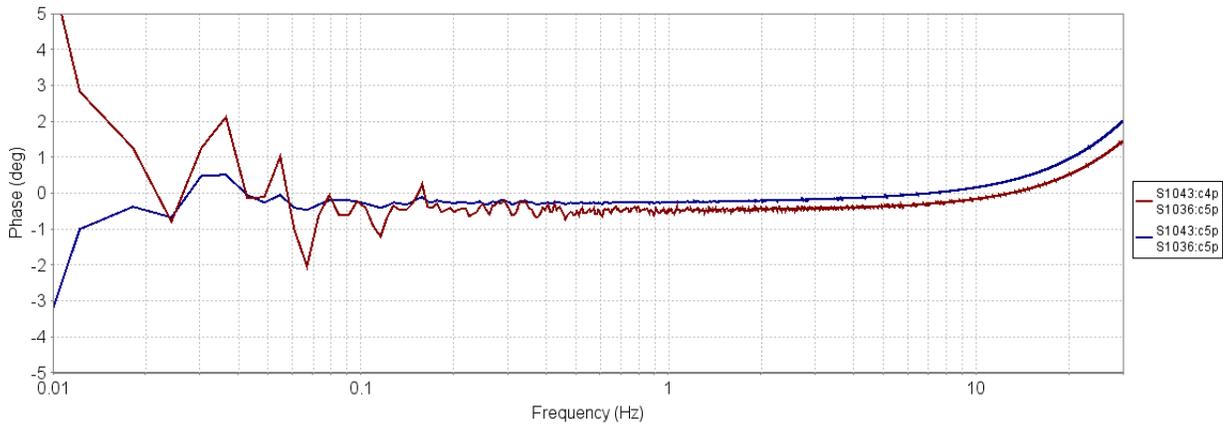


Figure 31 Calibrator White Noise Relative Phase, 0.01 – 28 Hz

Here we can see that the variation in magnitude and phase between calibrator input signal and each of the MB3a sensors are described in the table below.

Table 20 Calibrator White Noise Relative Magnitude and Phase, 0.01 – 28 Hz

	Magnitude, 0.01 – 28 Hz	Phase, 0.01 – 28 Hz
S1043:c4p (MB3a SN 52)	-0.75 dB / +0.75 dB	-2 deg / +5 deg
S1043:c5p (MB3a SN 30)	+0.75 dB / +0.3 dB	-3 deg / +2 deg

Examining the coherence, relative magnitude, and relative phase between the outputs of the two MB3a's results in the plots below.

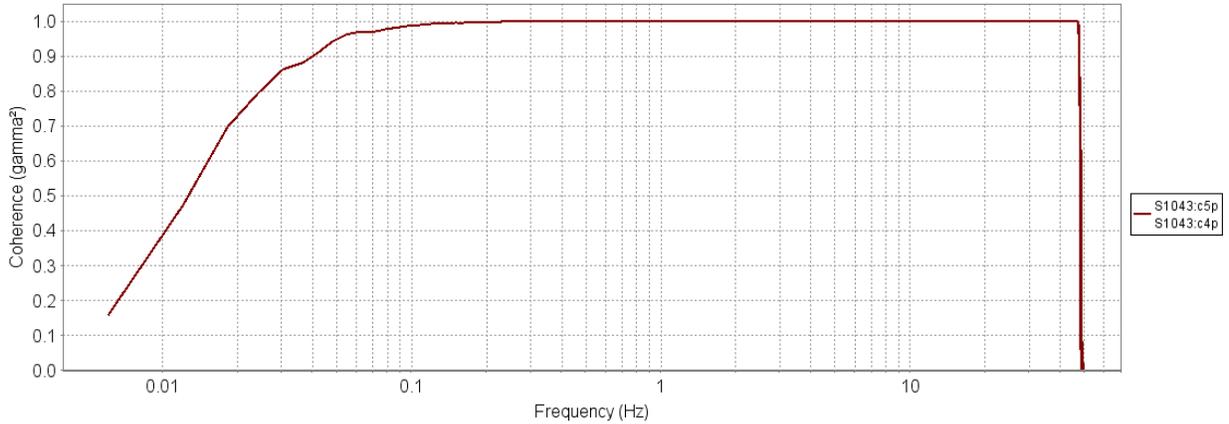


Figure 32 Calibrator White Noise MB3a vs MB3a Coherence

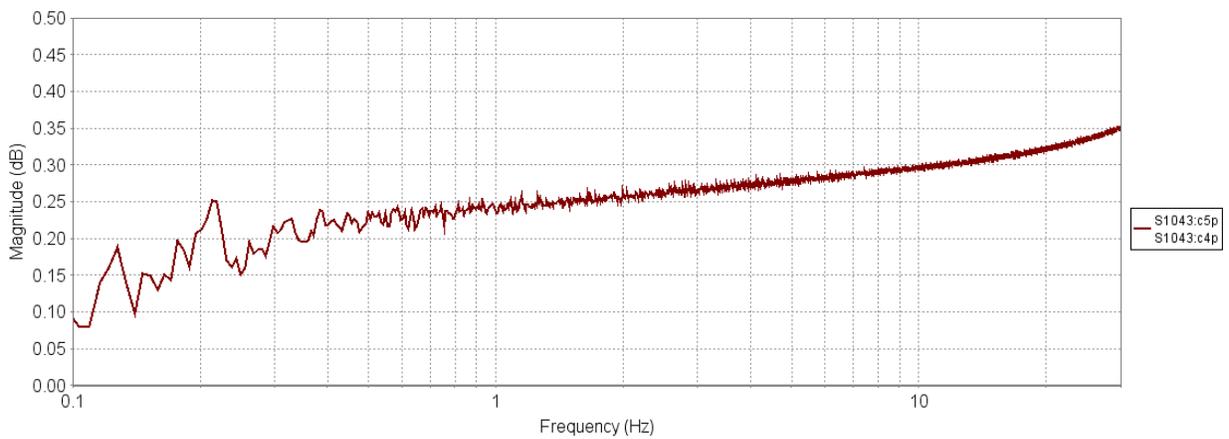


Figure 33 Calibrator White Noise MB3a vs MB3a Relative Magnitude, 0.1 – 28 Hz

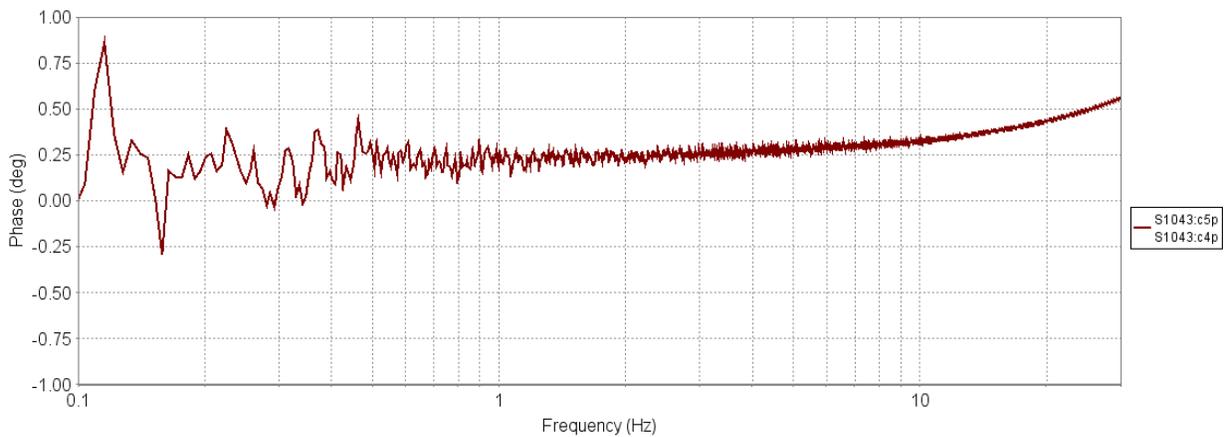


Figure 34 Calibrator White Noise MB3a vs MB3a Relative Phase, 0.1 – 28 Hz

We see that the outputs are highly coherent from 0.1 to above 40 Hz, for the white noise input signal we have provided to the calibrator. The relative magnitude ranges from +0.1 to +0.35 dB from 0.1 to 28 Hz, with a value of 0.24 dB at 1 Hz. The relative phase ranges from -0.25 to 0.9 degrees from 0.1 to 28 Hz, with a value of 0.25 degrees at 1 Hz.

3.11 Calibrator Harmonic Distortion

Test description: The purpose of the harmonic distortion test is to verify the linearity of the sensor using the sensor’s calibrator. A Quanterra ultra-low-distortion oscillator was used to generate a very pure sinusoid with a frequency of 1.41 Hz and amplitude of 0.5 V (3 Pa) for approximately 1 hour. This white noise signal was fed into both of the MB3’s calibrator inputs and simultaneously recorded on a second Smart24 testbed digitizer as a reference. The MB3a sensors were enclosed within the 330 L isolation chamber with their inlets open to help isolate them from ambient pressure signals.

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 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 0.80 dB. The power spectra of the time series was collected and analyzed to identify the fundamental frequency and all harmonics present (Merchant, 2011).

Note that the MB3a calibrator input is expecting a single-sided input signal. The Smart24 signal generator outputs a differential signal. To compensate, only the positive line and the ground line were connected to the MB3a calibrator input.

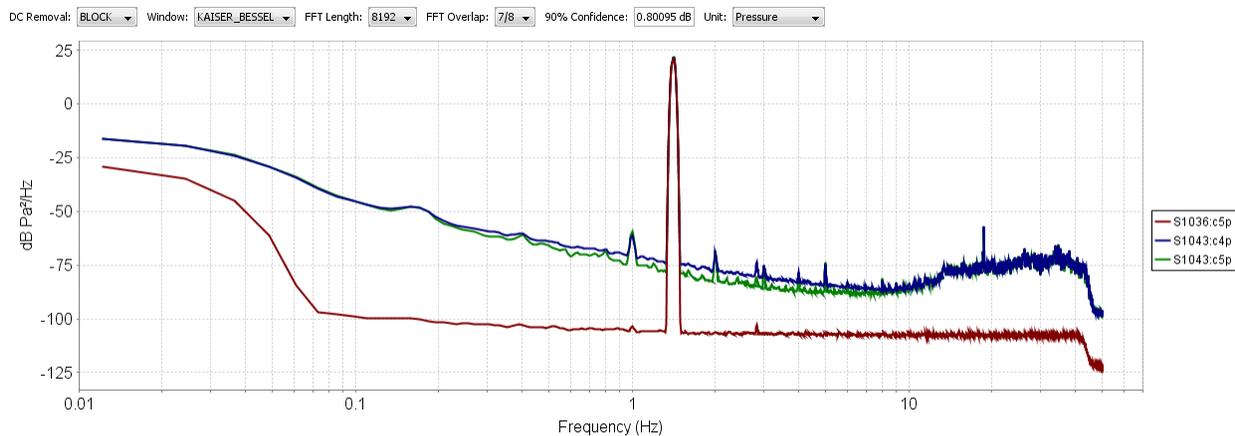


Figure 35 Calibrator Harmonic Distortion, 3 Pa

The reference signal appears as a very pure tone with a very slight integer hertz noise at 1 Hz and a single harmonic visible at 2.42 Hz. The output of the MB3a sensors has a tone with matching signal amplitudes but with somewhat more distortion both at integer hertz and at harmonics of 1.41 Hz. The amount of Total Harmonic Distortion (THD) present in each of the recorded signals is shown in the table below.

Table 21 Calibrator Harmonic Distortion, 3 Pa

Waveform	Peak RMS	Secondary RMS	THD
----------	----------	---------------	-----

S1036:c5p (reference)	2.02853 Pa rms	1.68253 uPa rms	-119.35877 dB
S1043:c4p (MB3a SN52)	2.11588 Pa rms	50.27558 uPa rms	-91.06134 dB
S1043:c5p (MB3a SN30)	2.17967 Pa rms	27.59045 uPa rms	-96.46911 dB

A second test of the harmonic distortion was performed in which the amplitude of the sinusoid was increased to 4 V peak (24 Pa). This test was run for approximately 3 minutes with a 90% confidence interval of 4.69 dB.

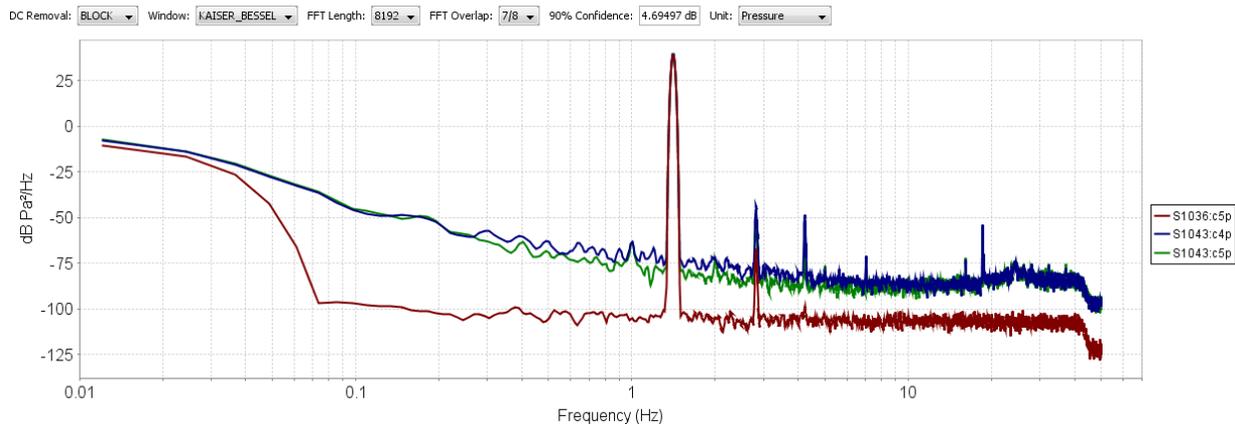


Figure 36 Calibrator Harmonic Distortion, 24 Pa

The reference signal appears as a very pure tone with harmonics visible at 2.42 Hz and 4.23 Hz. The output of the MB3a sensors has a tone with matching signal amplitudes but with more harmonics visible. The amount of Total Harmonic Distortion (THD) present in each of the recorded signals is shown in the table below.

Table 22 Calibrator Harmonic Distortion, 24 Pa

Waveform	Peak RMS	Secondary RMS	THD
S1036:c5p (reference)	16.23009 Pa rms	74.49199 uPa rms	-106.75797 dB
S1043:c4p (MB3a SN52)	16.96583 Pa rms	1.1268 mPa rms	-82.16396 dB
S1043:c5p (MB3a SN30)	17.44389 Pa rms	0.47311 mPa rms	-91.17929 dB

3.12 Calibrator 2-Tone

Test description: The purpose of the 2-Tone test is to verify the linearity of the sensor. A Quanterra ultra-low-distortion oscillator is used to generate a signal containing two tones. The first tone is a large amplitude (2 V), low frequency (0.01 Hz) sinusoid. The second tone is a smaller amplitude (0.5 V), higher frequency (1.23 Hz) sinusoid. This signal was fed into both of the MB3's calibrator inputs and simultaneously recorded on a second Smart24 testbed digitizer

as a reference. The MB3a sensors were enclosed within the 330 L isolation chamber with their inlets open to help isolate them from ambient pressure signals.

A sequence of 10 time windows for sine fits, each capturing 5 cycles of the 1.23 Hz tone, were then assigned across a half period of the low frequency sinusoid, as shown in the figure below.

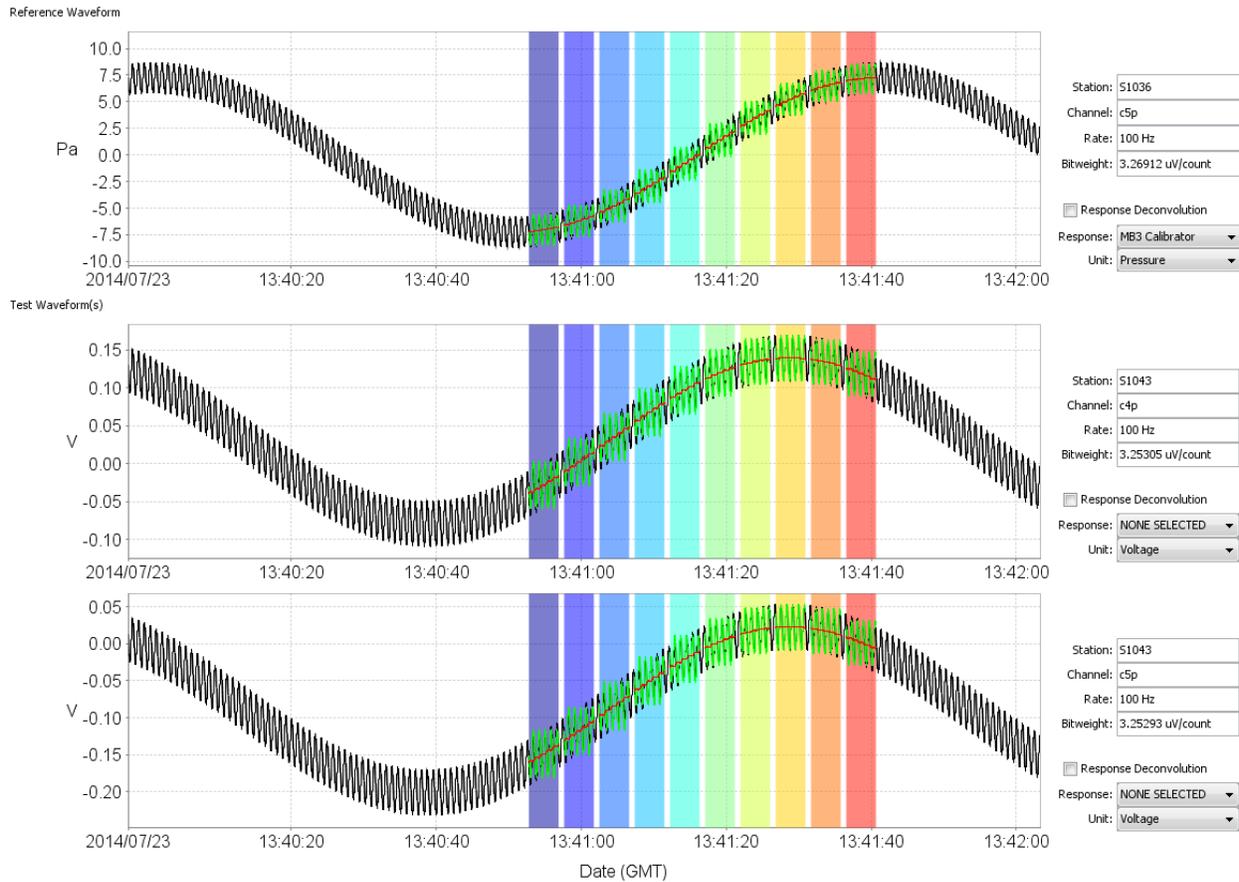


Figure 37 Calibrator 2-Tone Time Series

With the MB3a’s calibrator sensitivity of 6 Pa/V, the low and high frequency amplitudes should result in observed pressures of +/- 12 Pa and +/- 3 Pa, respectively. However, at low frequency tone of 0.01 Hz the MB3a response is down 3 dB, which would result in an expected output of +/- 8.5 Pa. This peak value is consistent with time series plot above.

There is an observable phase delay in the low frequency sinusoid between the signal being fed into the MB3a calibrator inputs and the output of the MB3a’s. This delay is expected since the response model for the MB3a at 0.01 Hz has an approximate 45 degree phase correction. The output time series have not been corrected for their respective instrument response models.

The time series were then filtered using a highpass Butterworth filter with a cutoff frequency of 50 mHz. This filter will serve to remove the low frequency signal from the time series.

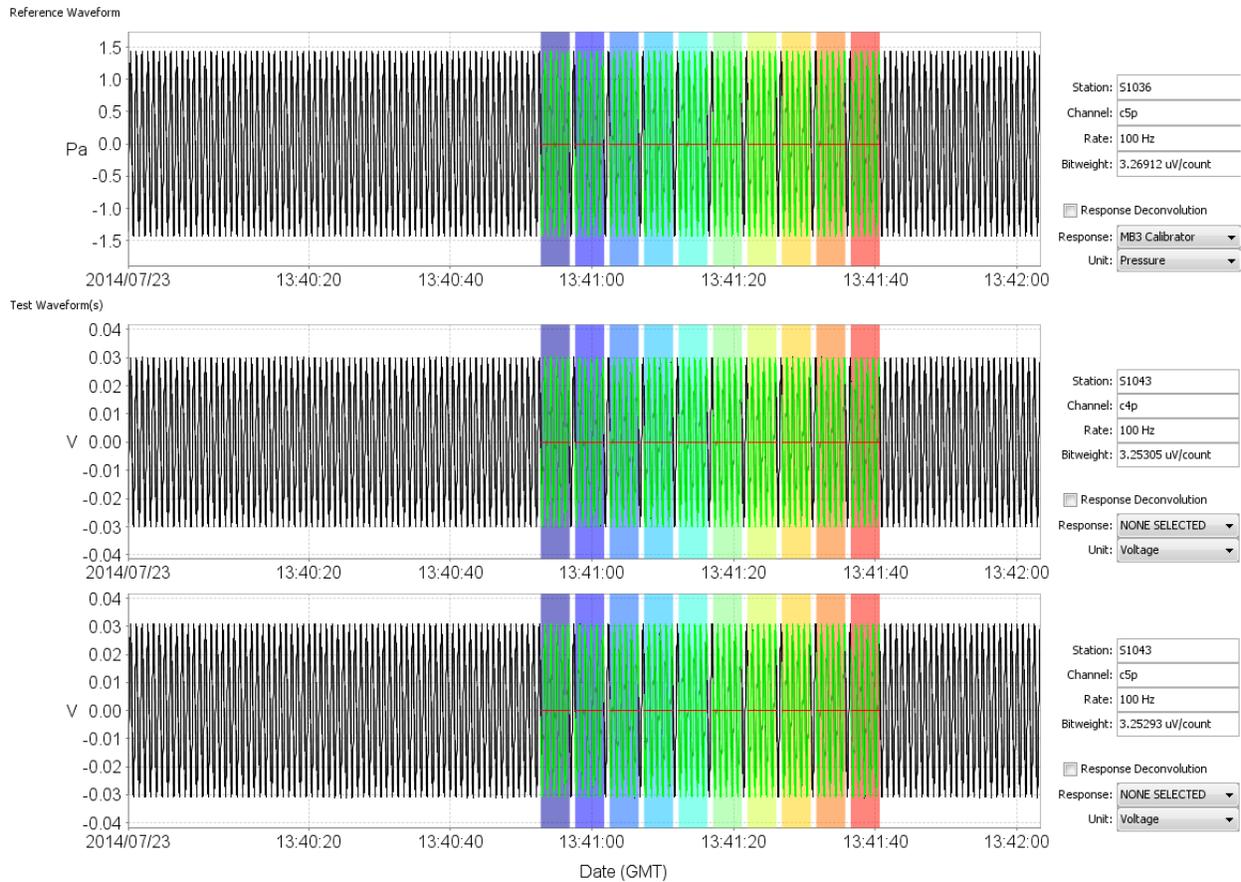


Figure 38 2-Tone Filtered Time Series

The pressure measurement for each of the tones was observed on the recording of the signal being inputted into the MB3a calibrator. The MB3a calibrator sensitivity of 6 Pa/V provided by CEA was used to convert the calibrator input voltage into a presumed reference pressure. 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.

The linearity of the MB3a’s may be determined by examining the estimated sensitivity for variations. If the MB3a is perfectly linear across the amplitude range of the input tone, then there should be no variation, to within measurement error, of the sensitivities.

Table 23 Calibrator 2-Tone Sensitivities

	1	2	3	4	5	6	7	8	9	10
S1043:c4p (MB3a SN 52)	20.86528 mV/Pa	20.8573 mV/Pa	20.86031 mV/Pa	20.86565 mV/Pa	20.86646 mV/Pa	20.85958 mV/Pa	20.86304 mV/Pa	20.86735 mV/Pa	20.8634 mV/Pa	20.86286 mV/Pa
S1043:c5p (MB3a SN 30)	21.49136 mV/Pa	21.48462 mV/Pa	21.49048 mV/Pa	21.4968 mV/Pa	21.49213 mV/Pa	21.49094 mV/Pa	21.49033 mV/Pa	21.49455 mV/Pa	21.49187 mV/Pa	21.49327 mV/Pa

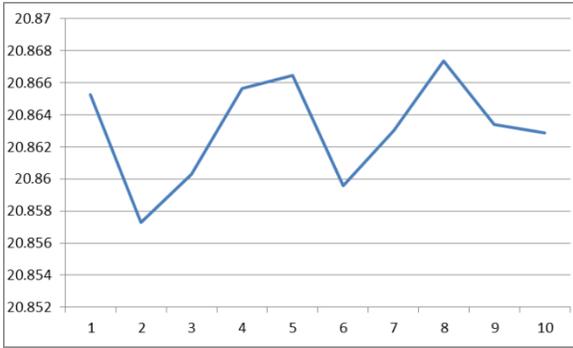


Figure 39 Calibrator 2-Tone Sensitivity MB3a SN52

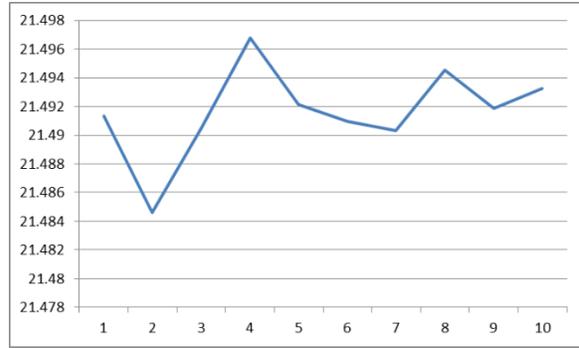


Figure 40 Calibrator 2-Tone Sensitivity MB3a SN30

MB3a SN52 was observed to have a mean sensitivity across the 2-Tone test of 20.8631 mV/Pa with a variation of +/- 0.0058 mV/Pa.

MB3a SN30 was observed to have a mean sensitivity across the 2-Tone test of 21.4916 mV/Pa with a variation of +/- 0.0070 mV/Pa.

The observed variation sensitivity in both sensors was less than 0.05%, which is below our measurement error. Therefore, using the calibrator, the two MB3a's appear to be linear across a +/- 12 Pa range of amplitudes.

3.13 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.

A vehicle was then driven around the FACT site bunker for approximately 5 minutes to generate the desired ground motion. The time series and power spectra of the MB2000, MB2005, and two MB3a sensors are shown below.

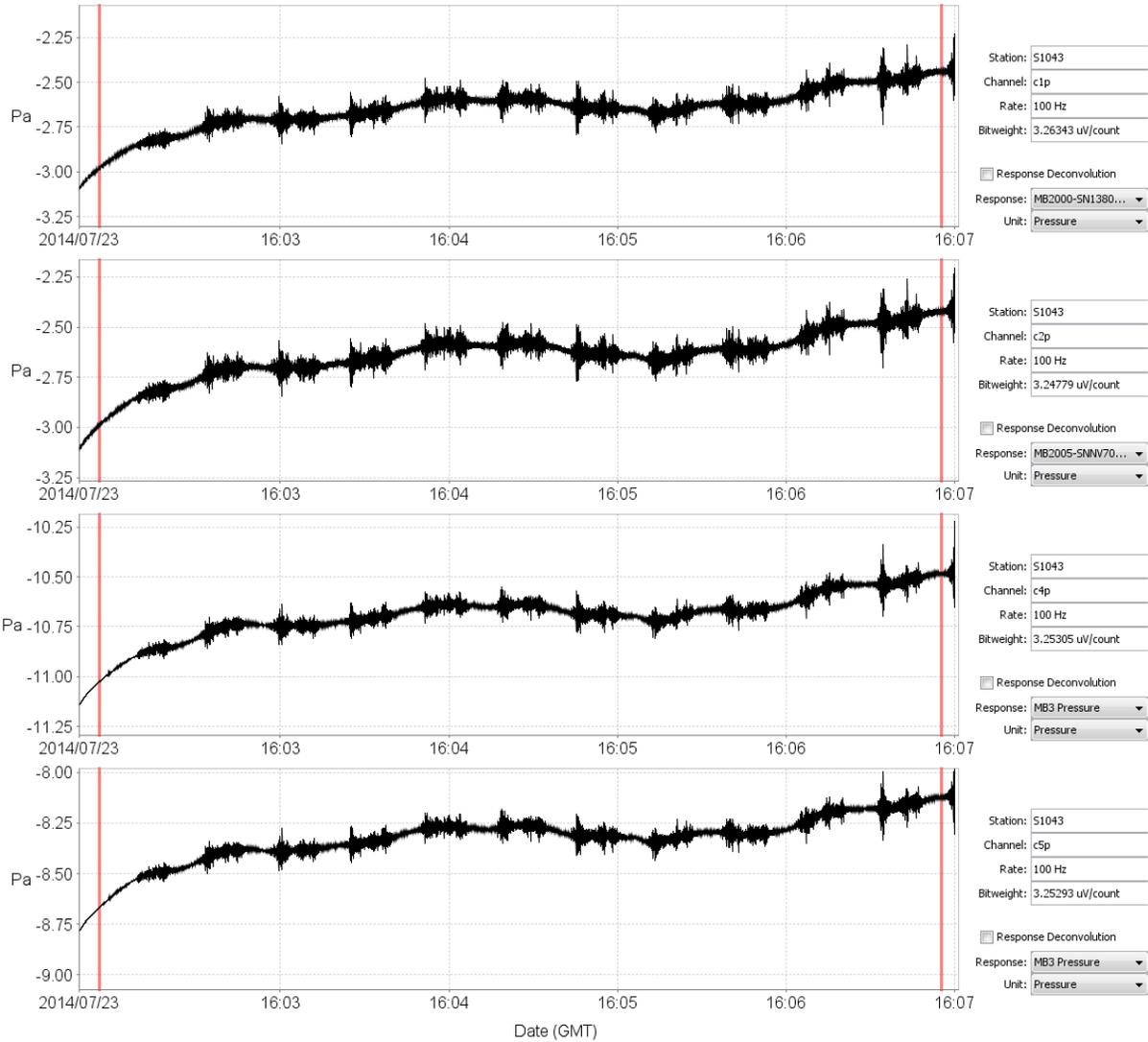


Figure 41 Pressure Time Series Due to Ground Motion

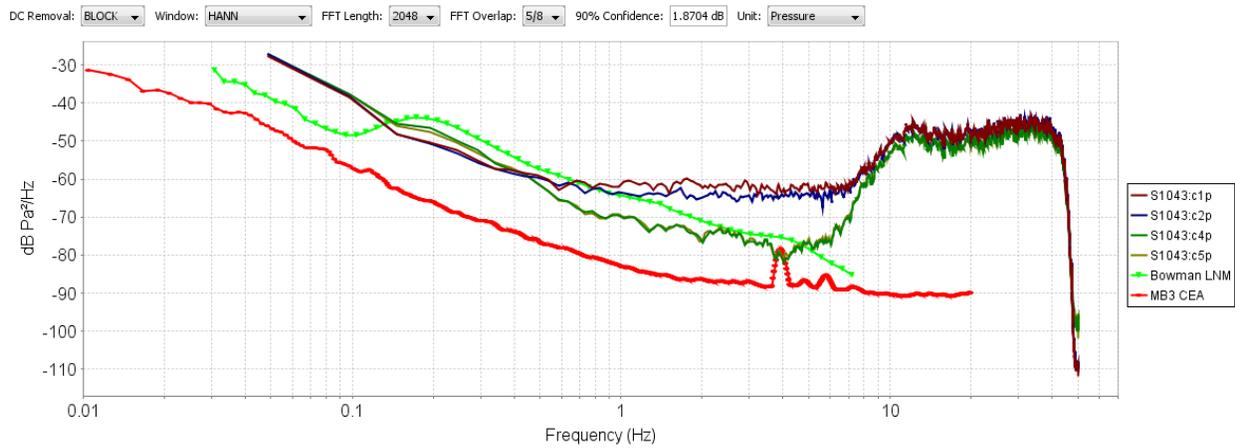


Figure 42 Pressure Power Spectra Due to Ground Motion

We see that the ground motion from the vehicle is clearly visible in the time series. In the power spectra, the ground motion is visible on the MB3a sensors at frequencies above 4 Hz when it becomes greater in magnitude than the observed background. The ground motion is not visible on the MB2000 or MB2005 until above 7 Hz due to their higher levels of self-noise than the MB3a.

The seismic sensitivity of the MB3a infrasound sensors is expected to be flat to acceleration. In order to evaluate their sensitivity, contrived seismic responses were created for each of the infrasound sensors. The data from the reference GS13 and the infrasound sensors were corrected for their respective instrument response models, scaling the records to acceleration (m/s^2) and correcting for amplitude and phase.

The coherence was computed using the technique described by Holcomb (1989) under the lumped noise model assumption, assigning incoherent noise to the infrasound sensors. The spectra (power spectral density estimates or PSDs) were computed using block-by-block DC removal, Hann windowing, 2048 FFT length and 5/8 window overlap. With the amount of data processed this provided a 90% confidence interval of 1.87 dB.

The sensitivities of the infrasound sensor seismic response models were then adjusted to minimize the relative magnitude between the data from the GS13 Seismometer and the infrasound sensors at 10 Hz. The resulting coherence and relative magnitude plots are shown below.

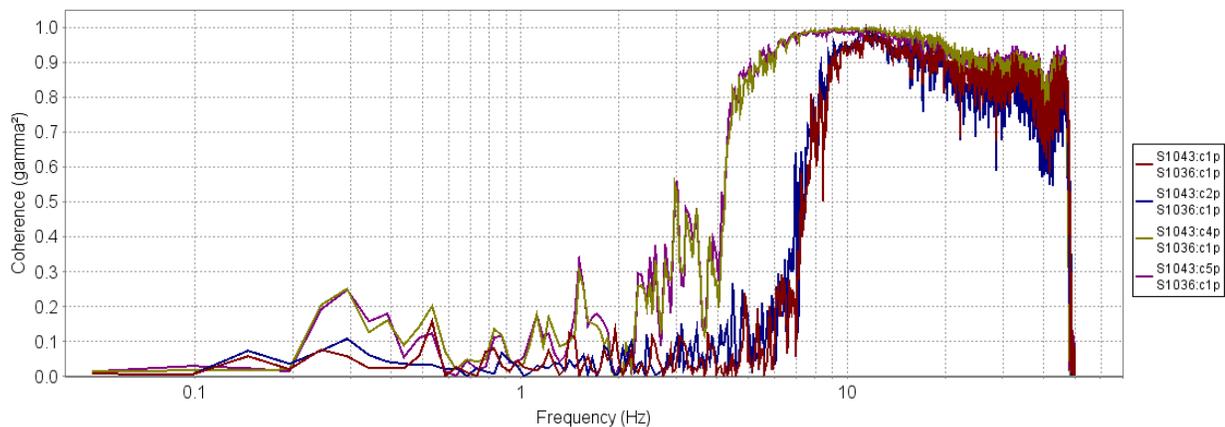


Figure 43 Ground Motion Coherence

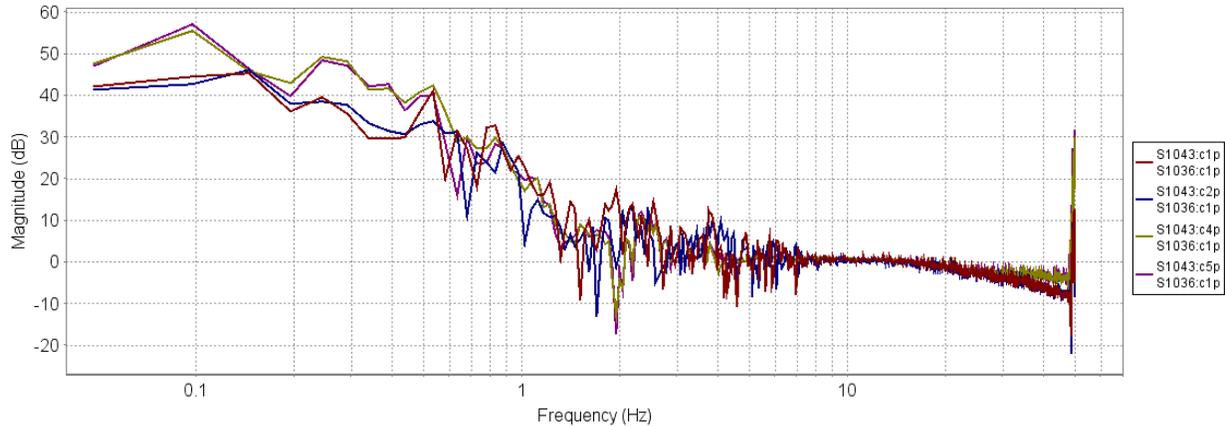


Figure 44 Ground Motion Magnitude Relative to the GS13 Seismometer

The identified seismic sensitivity values for the MB2000, MB2005, and MB3a are shown in the table below:

	Seismic Sensitivity at 10 Hz
MB2000 SN1380	4.2 V/m/s ²
MB2005 SN7009	4.2 V/m/s ²
MB3a SN52 and SN30	0.6 V/m/s ²

Figure 45 Infrasound Sensor Seismic Sensitivity

The MB3a specifications state that the seismic sensitivity is less than 30 Pa/m/s². Using the MB3a's nominal sensitivity of 20 mV/Pa, the seismic sensitivity specification is equivalent to 0.6 V/m/s², which is what we observed.

Note that the MB2000 and MB2005 that SNL uses as reference were specially ordered to have an electronic gain that results in a sensitivity of 100 mV/Pa rather than the standard 20 mV/Pa. So, to compare the seismic sensitivities of their transducers, it is necessary to divide the MB2000 and MB2005 seismic sensitivities in the table above by a factor of 5. That would make the 4.2 V/m/s² equivalent to 0.84 V/m/s².

So, the MB3a seismic sensitivity was measured to be 0.6 V/m/s² compared to the MB2000 and MB2005 seismic sensitivity of 0.84 V/m/s², a reduction of 28.6 % or 2.9 dB.

For comparison, the following plot of power spectra in ground acceleration was made using the isolation data (3.2 Isolation Noise) from the GS13 Seismometer and the seismic sensitivity responses of the infrasound sensors.

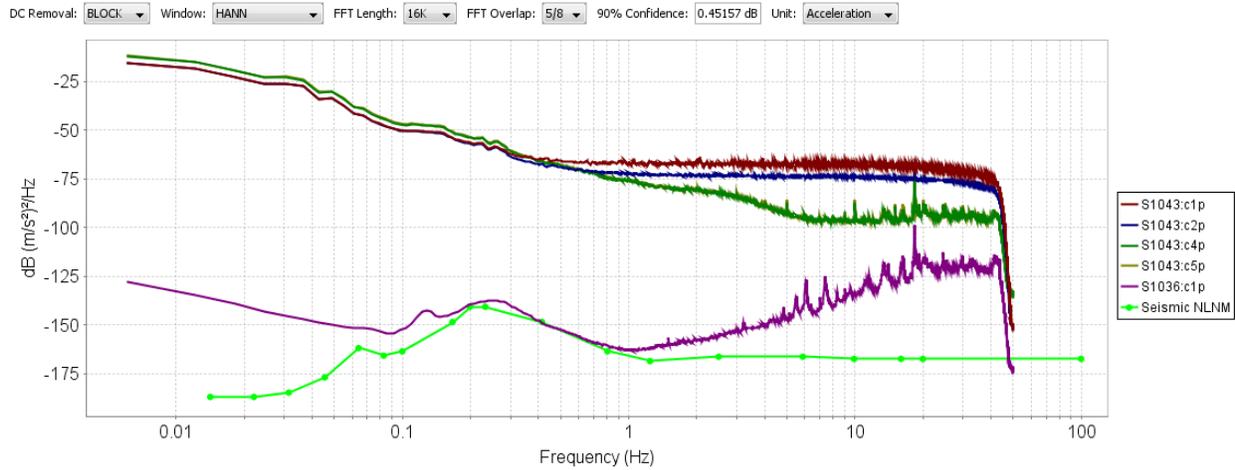


Figure 46 Ground Motion Power Spectra

This plot of ground motion is illustrative of the levels of ground acceleration needed to be visible on the output of the MB3a in a quiet pressure environment. The power spectra show the ground acceleration equivalent of the sensor output during a quiet period using their evaluated seismic sensitivities.

4 EVALUATION SUMMARY

Power:

The observed power consumption of the MB3a SN 30 and SN52 sensors were both approximately 122 mW at 13.2 V.

Isolation Noise:

The observed self-noise of the MB3a SN 30 and SN52 sensors were 36 dB below the noise level of 5 mPa/ $\sqrt{\text{Hz}}$ at 1 Hz, exceeding the IMS requirement of being at least 18 dB below. In addition, the MB3a self-noise is entirely below the Bowman LNM.

Dynamic Range:

The observed dynamic range of the MB3a SN30 and SN52 sensors was more than 115 dB across the 0.02 – 4 Hz passband. Across the entire 0.01 – 28 Hz pass band of the MB3, the estimated dynamic range exceeds 110 dB.

Frequency Amplitude Response Verification:

The observed sensitivity at 1 Hz of the MB3a SN30 and SN52 sensors were 21.20 mV/Pa and 20.30 mV/Pa, respectively. This represents a differed from the 20 mV/Pa nominal sensitivity of 6% (0.51 dB) and 1.5% (0.13 dB), respectively. The sensitivities were consistent across a range of amplitudes, from approximately 0.134 Pa to 4.6 Pa, differing by less than +/- 0.19% (0.016 dB). All observed variations in sensitivity across a frequency range of 0.01 to 10 Hz were consistent with the MB3a response model provided by CEA. Across the 0.02 – 4 Hz pass band, the observed sensitivities differed from the average by +/- 0.71% (0.061 dB) and +/- 0.89% (0.077 dB), respectively.

Frequency Amplitude Phase Verification:

Broadband measurements of a white noise source indicate that both the MB3a SN30 and SN52 sensors have a response that is flat across 0.02 – 4 Hz to within 0.25 dB in magnitude and 0.6 degrees in phase. The SN30 sensor has a magnitude response that is approximately 0.4 dB greater than SN52 across a 0.01 – 10 Hz pass band.

Dynamic Noise:

The observed self-noises of the MB3a SN30 and SN52 sensors, while measuring amplitudes as much as 70 dB above its noise model, were consistent with its noise model.

Harmonic Distortion:

The piston-phone harmonic distortion test identifies that the two MB3a SN30 and SN52 sensors have a linearity that is better than the -44 dB linearity of the piston-phone used in our test bed.

2-Tone:

The piston-phone 2-Tone test identifies that the two MB3a SN30 and SN52 sensors have a variation in sensitivity across amplitude which is less than 0.1 %, which is below measurement error, across a +/- 3 Pa range of amplitudes.

Calibrator Frequency Amplitude Response Verification:

The observed sensitivity using the calibrator at 1 Hz of the MB3a SN30 and SN52 sensors were 21.49 mV/Pa and 20.87 mV/Pa, respectively. This represents a difference from the 20 mV/Pa nominal sensitivity of 7.45% (0.62 dB) and 4.35% (0.37 dB), respectively. The sensitivities were consistent across a range of amplitudes, from approximately 1.5 Pa to 9 Pa, differing by less than +/- 0.29% (0.025 dB). All observed variations in sensitivity across frequency range of 0.01 to 10 Hz were consistent with the MB3a response model provided by CEA. Across the 0.02 – 4 Hz pass band, the observed sensitivities differed from the average by +/- 0.57% (0.049 dB) and +/- 1.21% (0.104 dB), respectively.

Calibrator Frequency Amplitude Phase Verification:

Broadband measurements of white noise into the calibrator indicate that both the MB3a SN30 and SN52 sensors have a response that is flat across 0.02 – 4 Hz to within 0.45 dB in magnitude and 1 degree in phase. The SN30 sensor has a magnitude response at 1 Hz that is approximately 0.24 dB greater than SN52.

Calibrator Harmonic Distortion:

Using ultra low distortion sinusoids into the calibrator, the two MB3a SN30 and SN52 sensors have a linearity that is in the range of -82 to -96.5 dB.

Calibrator 2-Tone:

The calibrator 2-Tone test identifies that the two MB3a SN30 and SN52 sensors have a variation in sensitivity across amplitude which is less than 0.05 %, which is below measurement error, across a +/- 12 Pa range of amplitudes.

Seismic Sensitivity:

The MB3a SN30 and SN52 sensors have a measured sensitivity to ground motion of 0.6 V/m/s². This is consistent with the MB3a specification of 30 Pa/m/s² with a pressure sensitivity of 20 mV/Pa. The MB3a seismic sensitivity is observed to be 28.6 % (2.9 dB) lower than the MB2000 and MB2005 reference sensors.

REFERENCES

1. CEA (May, 2014), *MB3a User Guide*.
2. 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.
3. 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.
4. IEEE Standard for Digitizing Waveform Recorders, IEEE Std. 1057-1994.
5. IEEE Standard for Analog to Digital Converters, IEEE Std. 1241-2001.
6. Kromer, Richard P., Hart, Darren M. and J. Mark Harris (2007), *Test Definition for the Evaluation of Infrasound Sensors Version 1.0*, SAND2007-5038.
7. McDonald, Timothy S. (1994), *Modified Noise Power Ratio Testing of High Resolution digitizers*, SAND94-0221.
8. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.
9. 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.

APPENDIX A: RESPONSES

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.

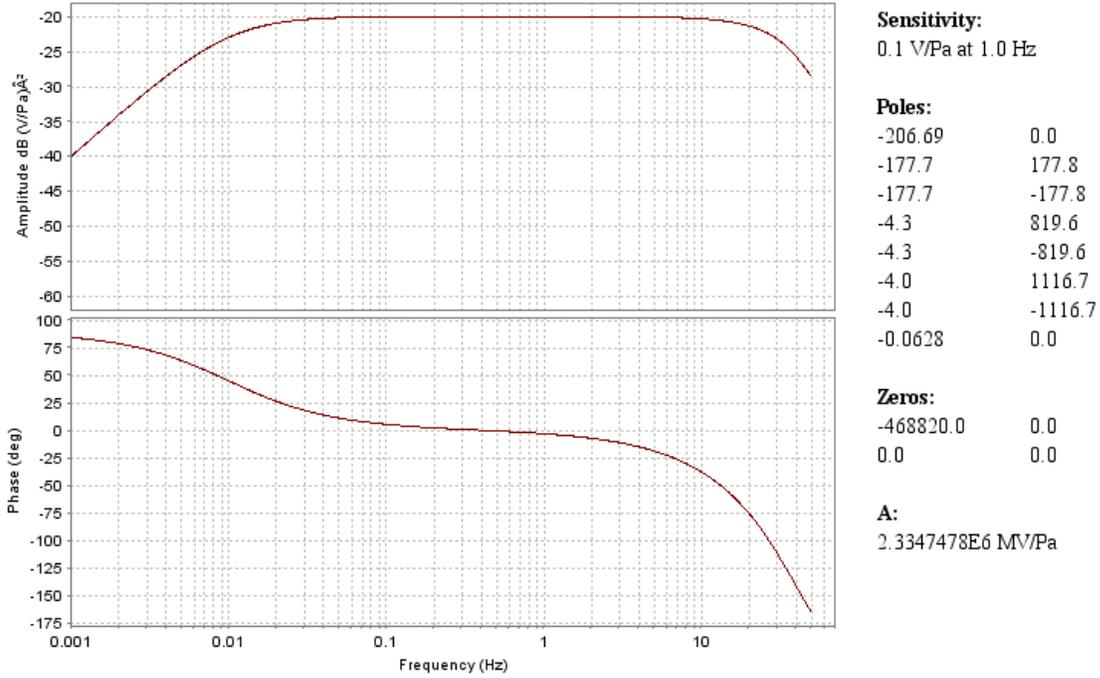


Figure 47 MB2000 Response

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.

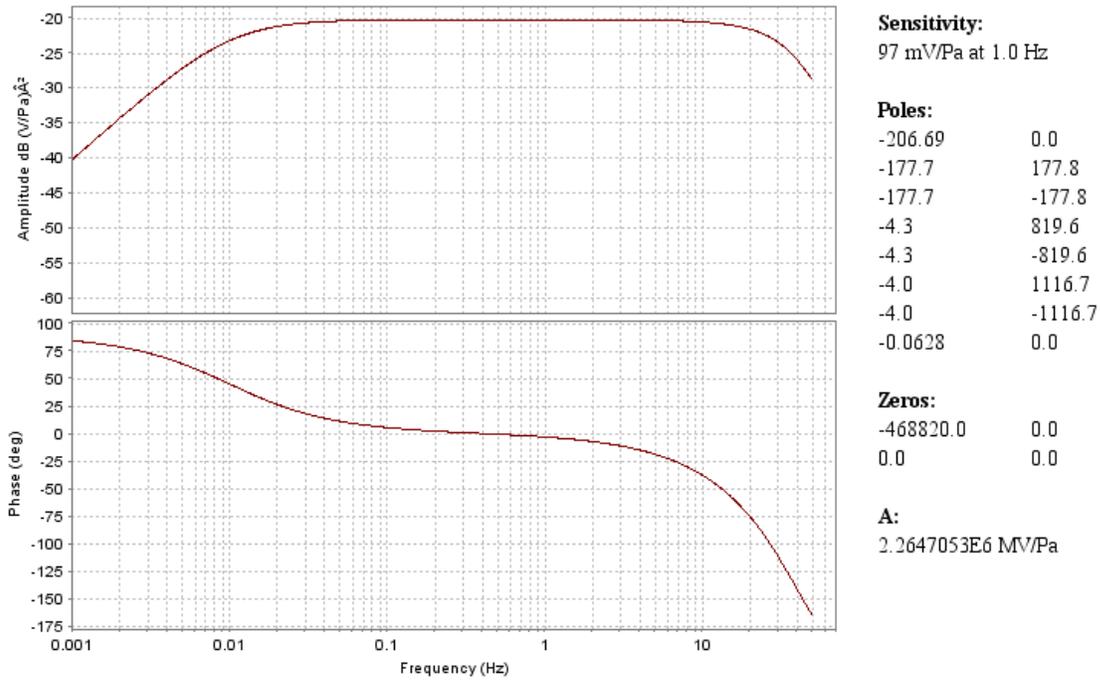


Figure 48 MB2005 Response

MB3a Response

The MB3a response was provided to SNL by CEA with the sensitivity, poles, and zeros below.

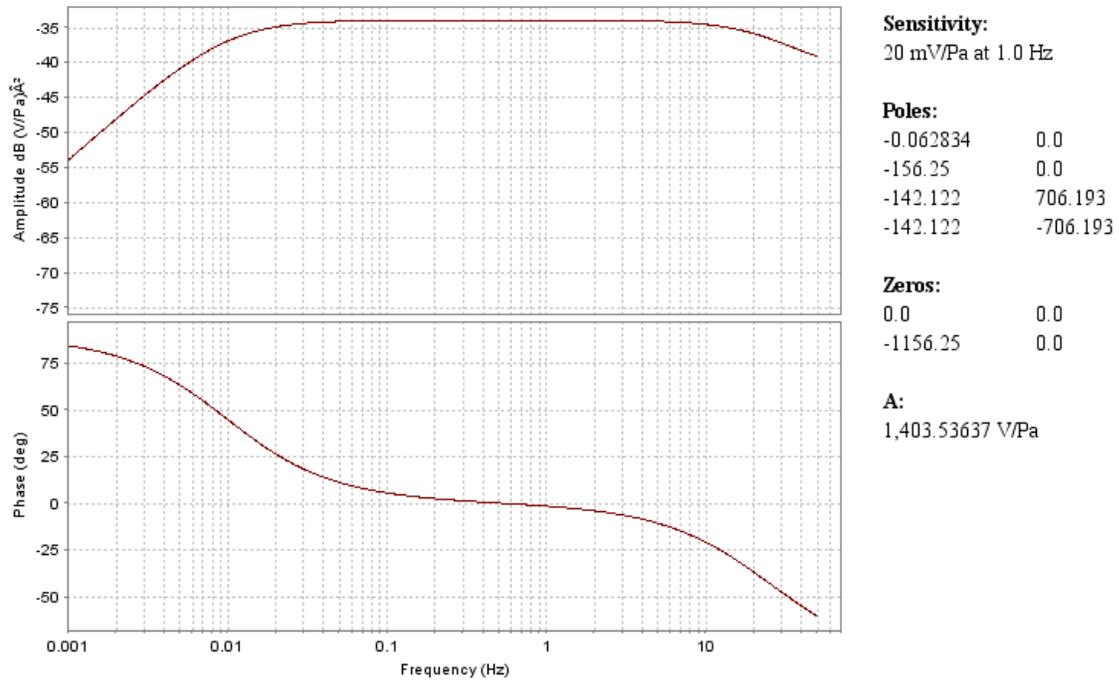


Figure 49 MB3a Response

DISTRIBUTION

- 1 Leslie Casey
U.S. Department of Energy/NNSA
Office of Nuclear Nonproliferation Research and Development (NA-222)
1000 Independence Avenue SW
Washington, DC 20585
- 1 Timothy Evans
U.S. Department of Energy/NNSA
Office of Nuclear Verification (NA-243)
1000 Independence Avenue SW
Washington, DC 20585
- 1 Dr. Terrill W. Ray
Office of Multilateral and Nuclear Affairs
Bureau of Arms Control, Verification, and Compliance
Room 5669
U.S. Department of State
2201 C St., N.W.
Washington, DC 20520
- 1 Julien Marty
Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)
Vienna International Centre
P.O. Box 1200
1400 Vienna, Austria
- 1 Philippe Millier
CEA
France
- 1 Guillaume Nief
CEA
France
- | | | | |
|---|--------|---------------------|------------------------|
| 1 | MS0404 | B. John Merchant | 05752 |
| 1 | MS0404 | Kyle D. McDowell | 05752 |
| 1 | MS0404 | Randy K. Rembold | 05752 |
| 1 | MS0404 | Neill P. Symons | 05752 |
| 1 | MS0404 | Mary Clare Stoddard | 06831 |
| 1 | MS0899 | Technical Library | 9536 (electronic copy) |



Sandia National Laboratories