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Hyperion 5113/GP Infrasound Sensor Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated an infrasound sensor, the 5113/GP manufactured by Hyperion. These infrasound sensors measure pressure output by a methodology developed by the University of Mississippi. The purpose of the infrasound sensor evaluation was to determine a measured sensitivity, transfer function, power, self-noise, dynamic range, and seismic sensitivity. These sensors are being evaluated prior to deployment by the U.S. Air Force.

ACKNOWLEDGMENTS

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

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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 Hyperion 5113/GP Infrasound Sensors

The evaluation of 4 Hyperion 5113/GP infrasound sensors, serial numbers 20141203.001, 20141203.002, 20141203.004, and 20141203.005, was performed by Sandia National Laboratories (SNL). The Hyperion 5113/GP sensors were manufactured by Hyperion Technology Group, Inc. These infrasound sensors measure pressure output by a methodology developed by the University of Mississippi. The purpose of this infrasound sensor evaluation was to determine a measured sensitivity, transfer function, power, self-noise, dynamic range, and seismic sensitivity compared against the manufacturer's specifications. These sensors are being evaluated prior to deployment by the U.S. Air Force.

2 TESTING OVERVIEW

2.1 Objectives

The objective of this work was to evaluate the overall technical performance of the 5113/GP infrasound sensor. Notable features of the 5113/GP include seismically decoupled transducer. 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.

2.4 Test and Evaluation Process

2.4.1 Infrasound Sensor Testing

Testing of the 5113/GP sensors was performed on April 15-22, 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.

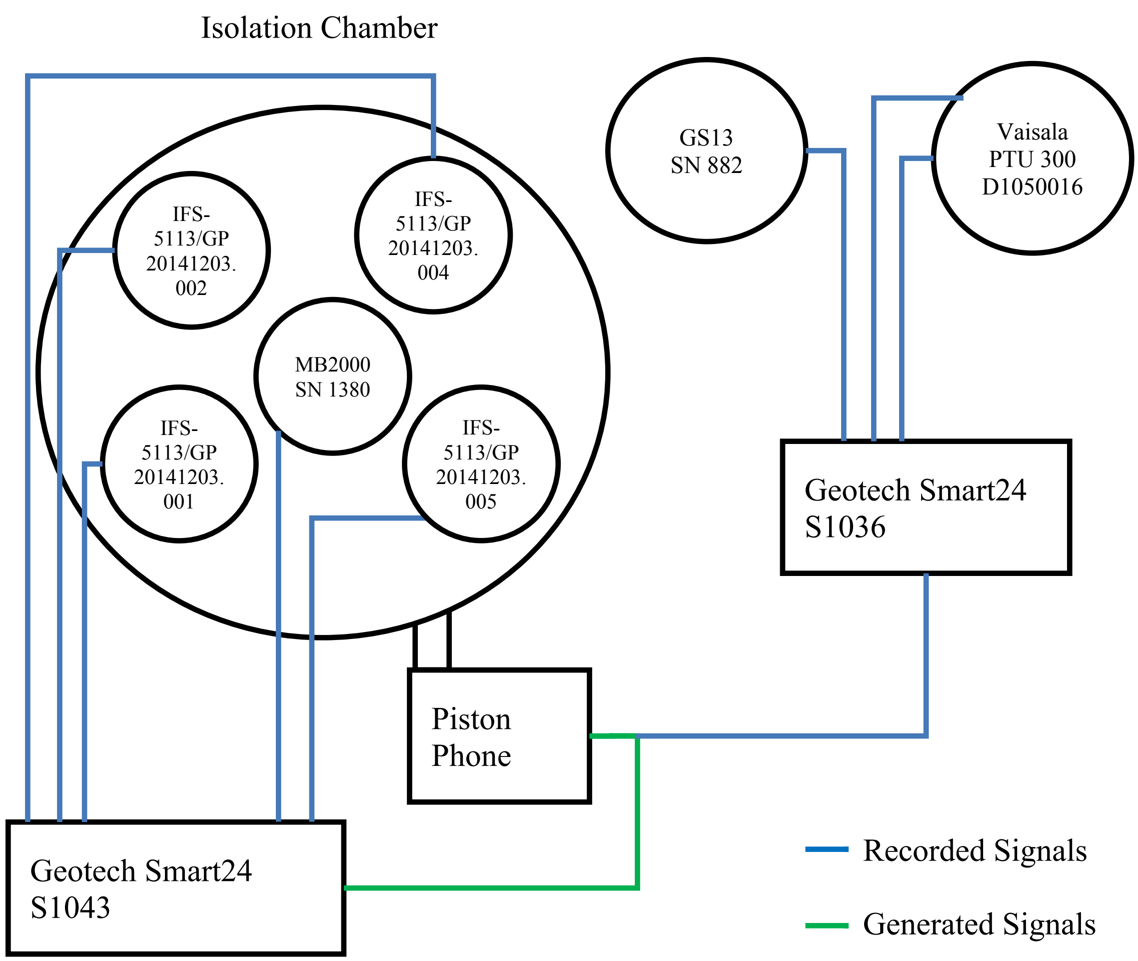

Figure 2 Test Configuration Diagram

Figure 3 Isolation Chamber, MB2000 Reference, Hyperion 5113/GP Sensors

Figure 4 GS13 Seismometer and Vaisala Pressure & Temperature Reference

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 more fully capture the pass band of the 5113/GP sensor and the 20 Hz rate data is representative of the typically infrasound 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 1 Geotech Smart24 Digitizer S1036 Configuration

Channel Name	Bitweight	Description
c1p / c1s	3.2773 uV/count	GS13 Vertical Seismometer
c4p / c4s	3.27781 uV/count	Signal Generator Output
c5p / c5s	3.27008 uV/count	Vaisala Ambient Pressure
c6p / c6s	3.27679 uV/count	Vaisala Ambient Temperature

Table 2 Geotech Smart24 Digitizer S1043 Configuration

Channel Name	Bitweight	Description
c1p / c1s	3.26431 uV/count	MB2000 SN1380
c2p / c2s	3.24886 uV/count	IFS-5113 20141203.001
c3p / c3s	3.25965 uV/count	IFS-5113 20141203.002
c4p / c4s	3.25398 uV/count	IFS-5113 20141203.004
c5p / c5s	3.25337 uV/count	IFS-5113 20141203.005

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 5113/GP 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 infrasound sensors under evaluation were provided by Hyperion Technology Group. The infrasound sensors were stated to have an output sensitivity of 100 mV/Pa and were designed for a differential output of 28 Volts peak to peak. The nominal sensitivity was used in the processing and analysis of all sensor data. The frequency passband is specified to be 0.01 – 100 Hz. The power input voltage range is 9-18 Volts DC, with reverse polarity protection.

2.5.6 Ambient Conditions

Testing of the Hyperion 5113/GP 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.

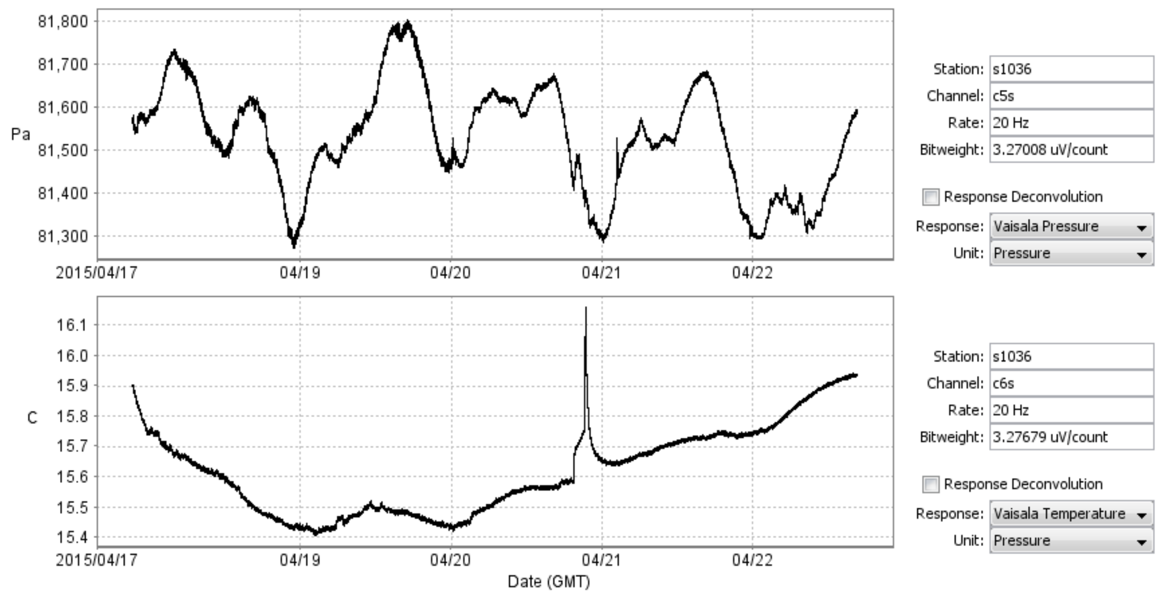

Figure 5 Ambient Pressure and Temperature

As may be seen in the plots, the mean atmospheric pressure during the testing was approximately 81,500 Pa with some variation in ambient pressure between 81,300 and 81,800 Pa during the days of testing.

The ambient temperature in the FACT bunker is very stable during the night with temperatures ranging between 15.4 and 15.9 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 9-18 V DC. The evaluation of the Hyperion 5113/GP 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 3 Hyperion 5113/GP Power Consumption

Sensor	Power Supply Voltage	Current	Power Consumption
IFS-5113/GP 20141203.001	13.09 V	108.0 mA	1.414 W
IFS-5113/GP 20141203.002	13.08 V	107.9 mA	1.411 W
IFS-5113/GP 20141203.004	13.09 V	119.5 mA	1.565 W
IFS-5113/GP 20141203.005	13.10 V	120.1 mA	1.563 W

The observed power consumption of the Hyperion 5113/GP was between approximately 1.41 and 1.56 W at 13.1 V. The stated power consumption from the sensor specifications was 1.5 W.

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 vertical red bars define start and end of the time window used in the self-noise analysis.

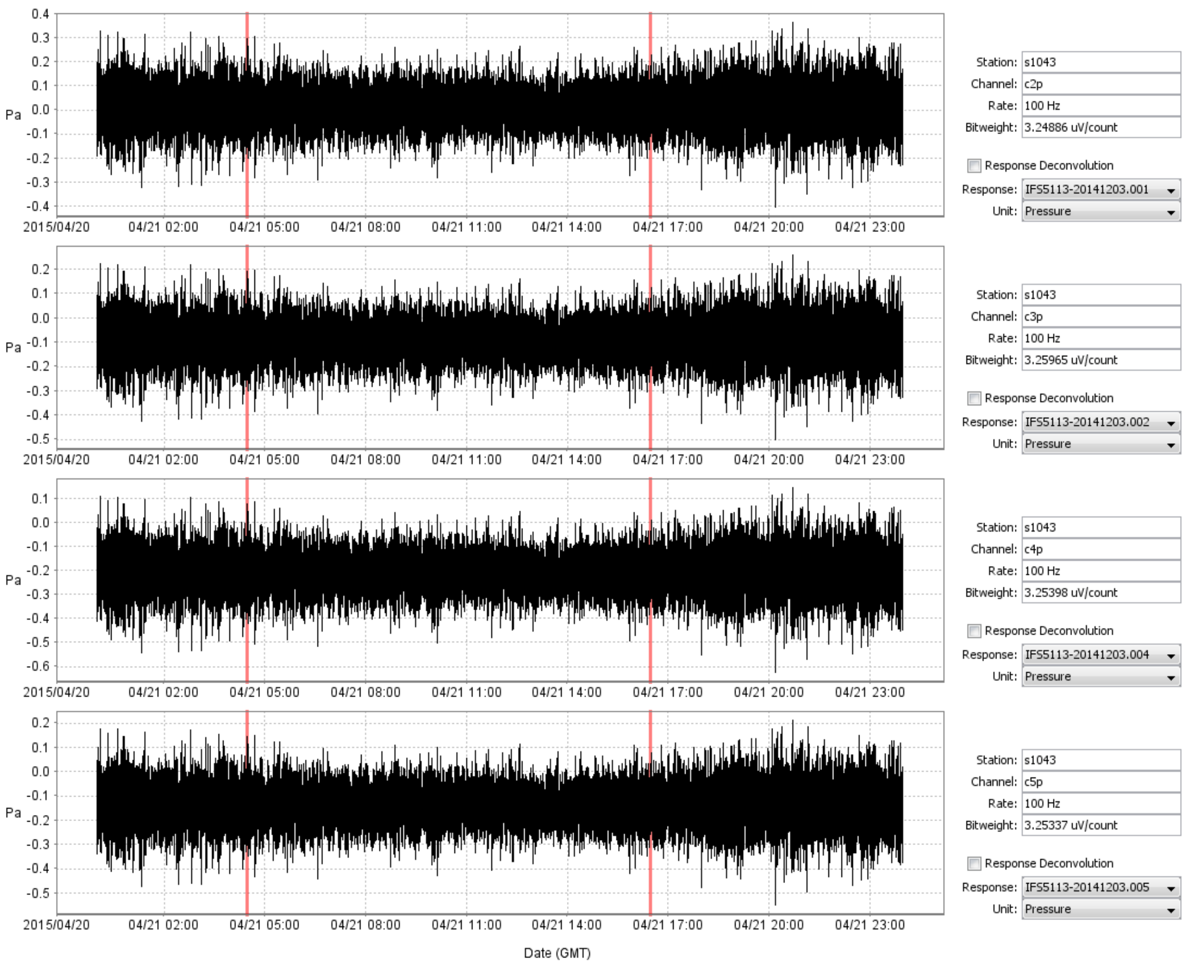

Figure 6 Hyperion 5113/GP Isolation Time Series

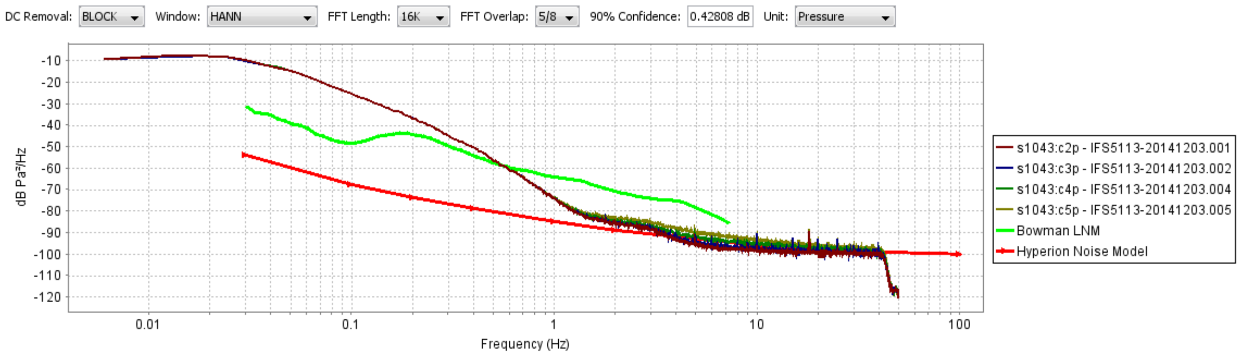

Figure 7 Hyperion 5113/GP Isolation Power Spectra

Even with the presence of the isolation chamber to attenuate signals, there remains some coherent signal between the 5113/GP sensors. This is a known limitation of the existing infrasound chamber. Therefore, the N-channel coherence technique was applied to the power spectra of the 5113/GP sensors to compute their incoherent noise, using a noise model that is able to unique identify the noise of each sensor. The 5113/GP noise, the Bowman Low Noise Model (LNM), and a noise model provided by Hyperion are shown on the plot below.

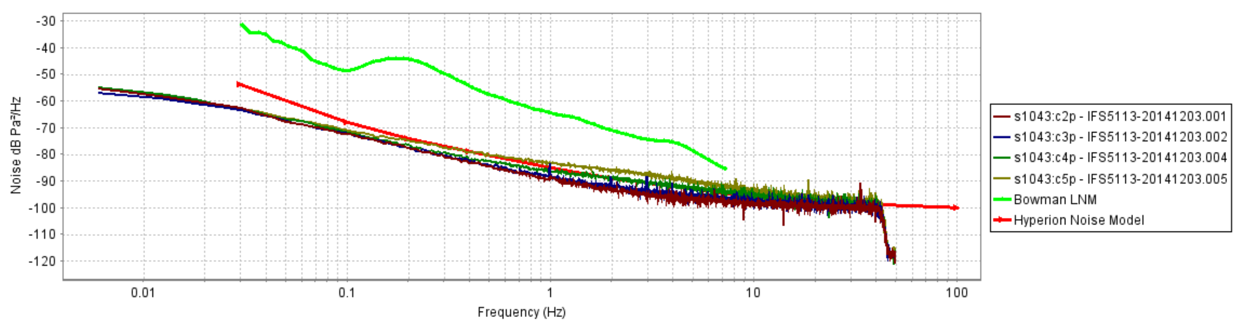

Figure 8 Hyperion 5113/GP Isolation Incoherent Self-Noise

As may be seen, the evaluated 5113/GP self-noise is consistent with the noise model provided by Hyperion. In addition, the 5113/GP 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 5113/GP 14 V clip level at 1 Hz are:

Table 4 Hyperion 5113/GP RMS Noise

Waveform	10 mHz - 40 Hz	20 mHz - 4 Hz
s1043:c2p - IFS5113-20141203.001	0.206 mPa rms	0.15444 mPa rms
s1043:c3p - IFS5113-20141203.002	0.20009 mPa rms	0.15255 mPa rms
s1043:c4p - IFS5113-20141203.004	0.23095 mPa rms	0.16928 mPa rms
s1043:c5p - IFS5113-20141203.005	0.25339 mPa rms	0.19475 mPa rms

Table 5 Hyperion 5113/GP Dynamic Range

Waveform	10 mHz - 40 Hz	20 mHz - 4 Hz
s1043:c2p - IFS5113-20141203.001	113.63504 dB	116.1372 dB
s1043:c3p - IFS5113-20141203.002	113.88789 dB	116.24424 dB
s1043:c4p - IFS5113-20141203.004	112.64208 dB	115.34028 dB
s1043:c5p - IFS5113-20141203.005	111.83663 dB	114.12262 dB

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 40 cycles of each tone were recorded; however, only 20 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
0.1 V	0.1345 Pa
0.5 V	0.7244 Pa
1 V	1.559 Pa
2 V	3.344 Pa
3 V	4.695 Pa

Table 7 Piston-phone Tone Frequencies

Frequencies
0.02 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 twice over a weekend to ensure they were correct when temperature variations, wind, and other man-made noise sources were minimal. The results from the two sequences are consistent. The results shown below were drawn from the two runs, selecting the set of frequency results from the run that had the least amount of background noise, allowing for a better sine fit.

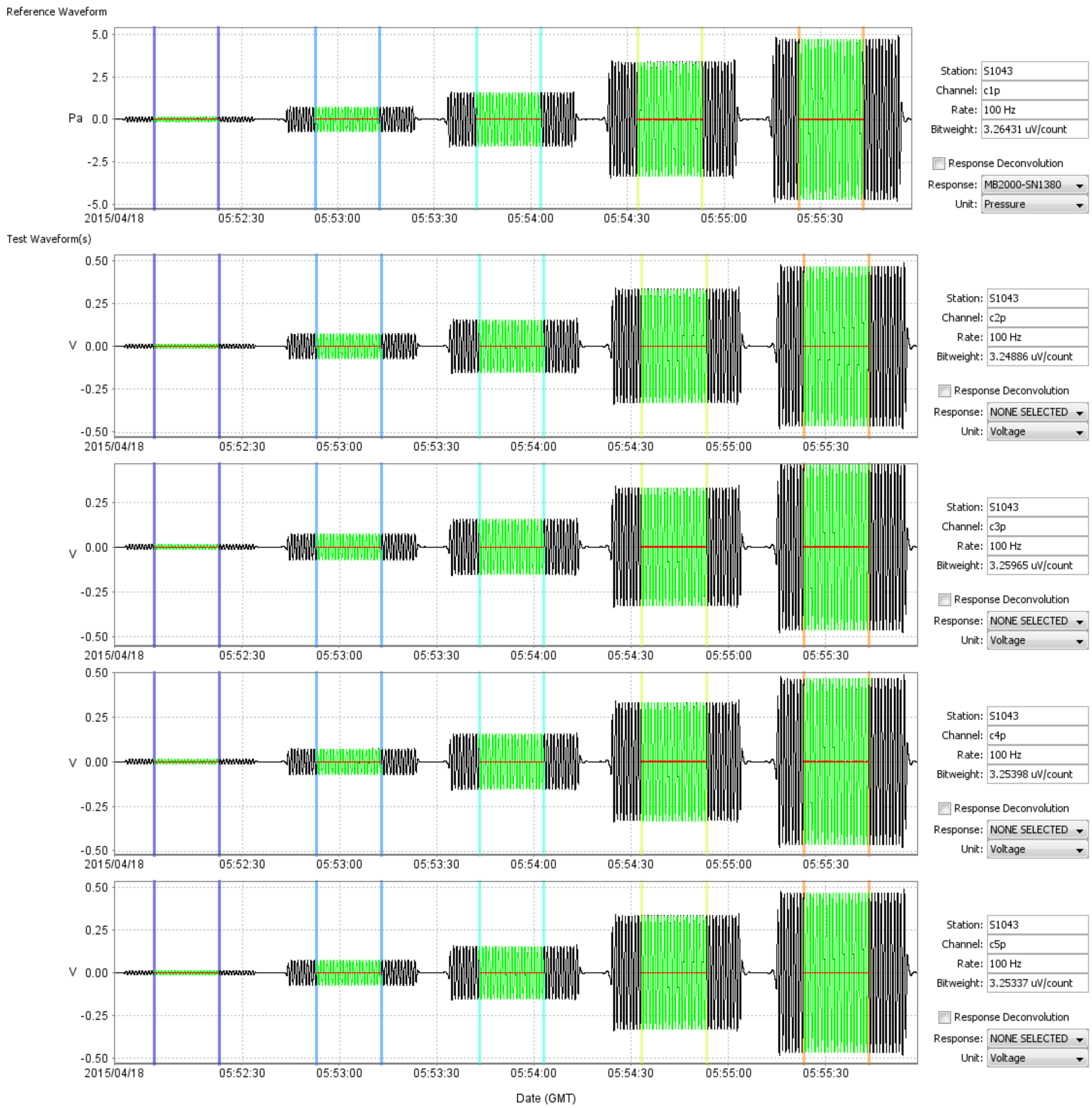

Figure 9 Piston-phone Tone Time Series for 1 Hz

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 bandpass filter centered on the frequency of the sine was applied to the waveform data to remove frequency content outside of the tone so as to improve the performance of the sine fit algorithm. The time windows 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 for 5113/GP 20141203.001

Pressure (at 1 Hz)	Theoretical (99.77 mV/Pa at 0.5 Hz)	0.1345 Pa	0.7244 Pa	1.559 Pa	3.344 Pa	4.695 Pa
0.02 Hz[2]	55.13 mV/Pa	53.13 mV/Pa	53.03 mV/Pa	53.20 mV/Pa	53.00 mV/Pa	53.16 mV/Pa
0.04 Hz[2]	80.16 mV/Pa	77.55 mV/Pa	77.88 mV/Pa	77.83 mV/Pa	77.89 mV/Pa	77.89 mV/Pa
0.08 Hz[2]	93.65 mV/Pa	93.16 mV/Pa	91.96 mV/Pa	91.90 mV/Pa	91.87 mV/Pa	91.91 mV/Pa
0.1 Hz[2]	95.78 mV/Pa	94.31 mV/Pa	94.31 mV/Pa	94.30 mV/Pa	94.30 mV/Pa	94.31 mV/Pa
0.2 Hz[2]	98.86 mV/Pa	97.61 mV/Pa	97.70 mV/Pa	97.71 mV/Pa	97.69 mV/Pa	97.69 mV/Pa
0.4 Hz[2]	99.67 mV/Pa	98.55 mV/Pa	98.65 mV/Pa	98.58 mV/Pa	98.63 mV/Pa	98.64 mV/Pa
0.8 Hz[1]	99.88 mV/Pa	98.30 mV/Pa	99.25 mV/Pa	98.91 mV/Pa	98.93 mV/Pa	98.92 mV/Pa
1 Hz[1]	99.90 mV/Pa	98.92 mV/Pa	98.87 mV/Pa	98.92 mV/Pa	98.93 mV/Pa	98.93 mV/Pa
2 Hz[2]	99.94 mV/Pa	98.55 mV/Pa	98.78 mV/Pa	98.76 mV/Pa	98.77 mV/Pa	98.76 mV/Pa
4 Hz[1]	99.94 mV/Pa	98.56 mV/Pa	98.51 mV/Pa	98.71 mV/Pa	98.71 mV/Pa	98.62 mV/Pa
8 Hz[2]	99.95 mV/Pa	98.44 mV/Pa	98.04 mV/Pa	97.93 mV/Pa	97.97 mV/Pa	97.97 mV/Pa
10 Hz[2]	99.95 mV/Pa	97.28 mV/Pa	97.53 mV/Pa	97.51 mV/Pa	97.55 mV/Pa	97.53 mV/Pa

Table 9 Piston-phone Sensitivities for 5113/GP 20141203.002

Pressure (at 1 Hz)	Theoretical (100.08 mV/Pa at 0.5 Hz)	0.1345 Pa	0.7244 Pa	1.559 Pa	3.344 Pa	4.695 Pa
0.02 Hz[2]	55.30 mV/Pa	52.41 mV/Pa	52.73 mV/Pa	52.57 mV/Pa	52.64 mV/Pa	52.66 mV/Pa
0.04 Hz[2]	80.41 mV/Pa	77.22 mV/Pa	77.57 mV/Pa	77.52 mV/Pa	77.59 mV/Pa	77.58 mV/Pa
0.08 Hz[2]	93.95 mV/Pa	93.13 mV/Pa	91.85 mV/Pa	91.83 mV/Pa	91.83 mV/Pa	91.82 mV/Pa
0.1 Hz[2]	96.08 mV/Pa	94.22 mV/Pa	94.26 mV/Pa	94.28 mV/Pa	94.26 mV/Pa	94.25 mV/Pa
0.2 Hz[2]	99.17 mV/Pa	97.64 mV/Pa	97.73 mV/Pa	97.74 mV/Pa	97.71 mV/Pa	97.71 mV/Pa
0.4 Hz[2]	99.98 mV/Pa	98.58 mV/Pa	98.69 mV/Pa	98.61 mV/Pa	98.67 mV/Pa	98.67 mV/Pa
0.8 Hz[1]	100.19 mV/Pa	98.32 mV/Pa	99.28 mV/Pa	98.94 mV/Pa	98.96 mV/Pa	98.95 mV/Pa
1 Hz[1]	100.21 mV/Pa	98.94 mV/Pa	98.89 mV/Pa	98.95 mV/Pa	98.95 mV/Pa	98.95 mV/Pa
2 Hz[2]	100.25 mV/Pa	98.56 mV/Pa	98.79 mV/Pa	98.76 mV/Pa	98.77 mV/Pa	98.76 mV/Pa
4 Hz[1]	100.25 mV/Pa	98.59 mV/Pa	98.52 mV/Pa	98.72 mV/Pa	98.73 mV/Pa	98.63 mV/Pa
8 Hz[2]	100.26 mV/Pa	98.50 mV/Pa	98.11 mV/Pa	97.99 mV/Pa	98.03 mV/Pa	98.04 mV/Pa
10 Hz[2]	100.26 mV/Pa	97.40 mV/Pa	97.65 mV/Pa	97.63 mV/Pa	97.67 mV/Pa	97.64 mV/Pa

Table 10 Piston-phone Sensitivities for 5113/GP 20141203.004

Pressure (at 1 Hz)	Theoretical (100.21 mV/Pa at 0.5Hz)	0.1345 Pa	0.7244 Pa	1.559 Pa	3.344 Pa	4.695 Pa
0.02 Hz[2]	55.37 mV/Pa	53.19 mV/Pa	53.41 mV/Pa	53.51 mV/Pa	53.45 mV/Pa	53.36 mV/Pa
0.04 Hz[2]	80.51 mV/Pa	77.86 mV/Pa	78.19 mV/Pa	78.14 mV/Pa	78.21 mV/Pa	78.20 mV/Pa
0.08 Hz[2]	94.07 mV/Pa	93.44 mV/Pa	92.23 mV/Pa	92.16 mV/Pa	92.14 mV/Pa	92.17 mV/Pa
0.1 Hz[2]	96.21 mV/Pa	94.55 mV/Pa	94.59 mV/Pa	94.59 mV/Pa	94.58 mV/Pa	94.59 mV/Pa
0.2 Hz[2]	99.30 mV/Pa	97.88 mV/Pa	97.97 mV/Pa	97.97 mV/Pa	97.95 mV/Pa	97.95 mV/Pa
0.4 Hz[2]	100.11 mV/Pa	98.79 mV/Pa	98.91 mV/Pa	98.83 mV/Pa	98.89 mV/Pa	98.89 mV/Pa
0.8 Hz[1]	100.32 mV/Pa	98.55 mV/Pa	99.50 mV/Pa	99.16 mV/Pa	99.17 mV/Pa	99.16 mV/Pa
1 Hz[1]	100.34 mV/Pa	99.18 mV/Pa	99.11 mV/Pa	99.17 mV/Pa	99.17 mV/Pa	99.17 mV/Pa
2 Hz[2]	100.38 mV/Pa	98.81 mV/Pa	99.03 mV/Pa	98.99 mV/Pa	99.01 mV/Pa	99.00 mV/Pa
4 Hz[1]	100.38 mV/Pa	98.78 mV/Pa	98.72 mV/Pa	98.92 mV/Pa	98.93 mV/Pa	98.83 mV/Pa
8 Hz[2]	100.39 mV/Pa	98.55 mV/Pa	98.16 mV/Pa	98.05 mV/Pa	98.09 mV/Pa	98.09 mV/Pa
10 Hz[2]	100.39 mV/Pa	97.34 mV/Pa	97.59 mV/Pa	97.56 mV/Pa	97.60 mV/Pa	97.58 mV/Pa

Table 11 Piston-phone Sensitivities for 5113/GP 20141203.005

Pressure (at 1 Hz)	Theoretical (100.21 mV/Pa at 0.5 Hz)	0.1345 Pa	0.7244 Pa	1.559 Pa	3.344 Pa	4.695 Pa
0.02 Hz[2]	55.37 mV/Pa	52.28 mV/Pa	52.76 mV/Pa	52.76 mV/Pa	52.63 mV/Pa	52.47 mV/Pa
0.04 Hz[2]	80.51 mV/Pa	77.22 mV/Pa	77.55 mV/Pa	77.50 mV/Pa	77.56 mV/Pa	77.56 mV/Pa
0.08 Hz[2]	94.07 mV/Pa	93.11 mV/Pa	91.86 mV/Pa	91.86 mV/Pa	91.86 mV/Pa	91.87 mV/Pa
0.1 Hz[2]	96.21 mV/Pa	94.32 mV/Pa	94.33 mV/Pa	94.33 mV/Pa	94.33 mV/Pa	94.32 mV/Pa
0.2 Hz[2]	99.30 mV/Pa	97.78 mV/Pa	97.85 mV/Pa	97.86 mV/Pa	97.83 mV/Pa	97.83 mV/Pa
0.4 Hz[2]	100.11 mV/Pa	98.76 mV/Pa	98.86 mV/Pa	98.78 mV/Pa	98.84 mV/Pa	98.84 mV/Pa
0.8 Hz[1]	100.32 mV/Pa	98.53 mV/Pa	99.51 mV/Pa	99.18 mV/Pa	99.20 mV/Pa	99.19 mV/Pa
1 Hz[1]	100.34 mV/Pa	99.22 mV/Pa	99.15 mV/Pa	99.20 mV/Pa	99.20 mV/Pa	99.20 mV/Pa
2 Hz[2]	100.38 mV/Pa	98.80 mV/Pa	99.03 mV/Pa	99.00 mV/Pa	99.02 mV/Pa	99.01 mV/Pa
4 Hz[1]	100.38 mV/Pa	98.74 mV/Pa	98.68 mV/Pa	98.89 mV/Pa	98.89 mV/Pa	98.79 mV/Pa
8 Hz[2]	100.39 mV/Pa	98.12 mV/Pa	97.72 mV/Pa	97.61 mV/Pa	97.65 mV/Pa	97.65 mV/Pa
10 Hz[2]	100.39 mV/Pa	96.61 mV/Pa	96.86 mV/Pa	96.85 mV/Pa	96.88 mV/Pa	96.86 mV/Pa

1. Results obtained from the first run
2. Results obtained from the second run

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

Table 12 Piston-phone Average Sensitivities

	Average Sensitivity at 1 Hz.	Difference from Nominal Sensitivity at 1 Hz.	Maximum difference from average at 1 Hz across 0.1345 – 4.695 Pa
5113/GP 20141203.001	98.91 mV/Pa	1.0% (0.04 dB)	0.05% (0.002 dB)
5113/GP 20141203.002	98.93 mV/Pa	1.29% (0.06 dB)	0.05% (0.002 dB)
5113/GP 20141203.004	99.16 mV/Pa	1.19% (0.05 dB)	0.05% (0.002 dB)
5113/GP 20141203.005	99.20 mV/Pa	1.15% (0.05 dB)	0.05% (0.002 dB)

The sensitivities of the 5113/GP sensors were observed to be between 98.9 and 99.2 mV/Pa. The observed sensitivity values differed from each sensors nominal sensitivity on the manufacturer's calibration sheet by between 1.0% and 1.29%. All sensors were flat across the 0.1345 – 4.695 Pa amplitude range to within +/- 0.05% (0.002 dB). The variation in sensitivity observed across frequency was consistent with the magnitude response roll off provided by the manufacturer with the reduction in sensitivity by half at approximately 0.02 Hz.

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 0.607 dB.

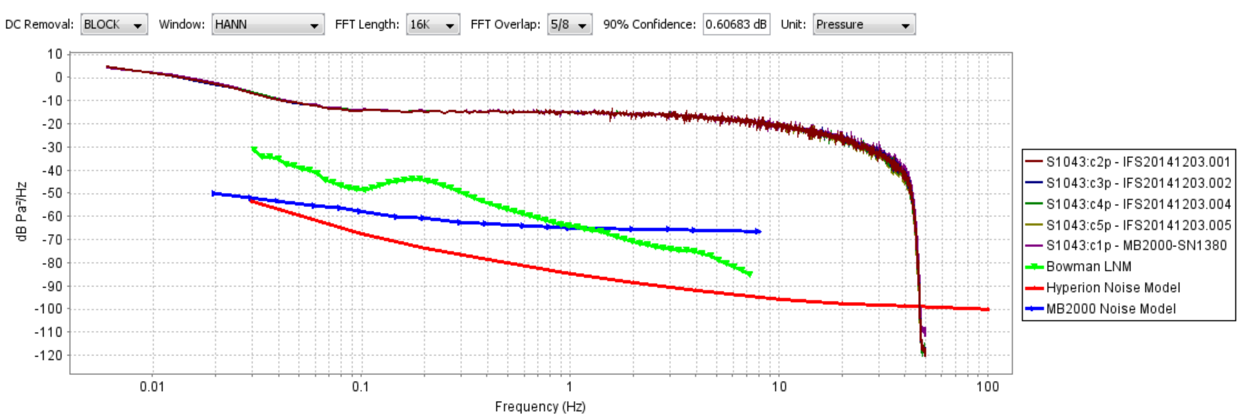

Figure 10 Piston-phone White Noise Power Spectra

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 5113/GP sensors under evaluation are plotted below.

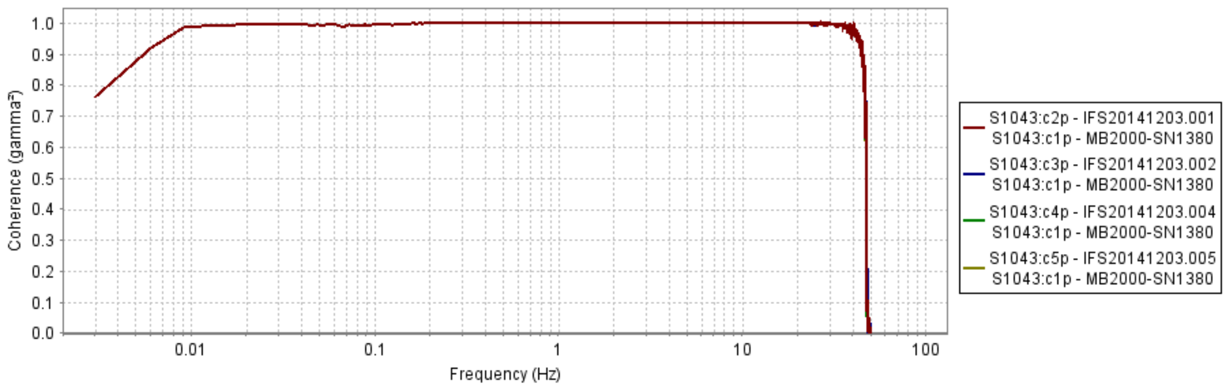

Figure 11 Piston-phone White Noise Coherence

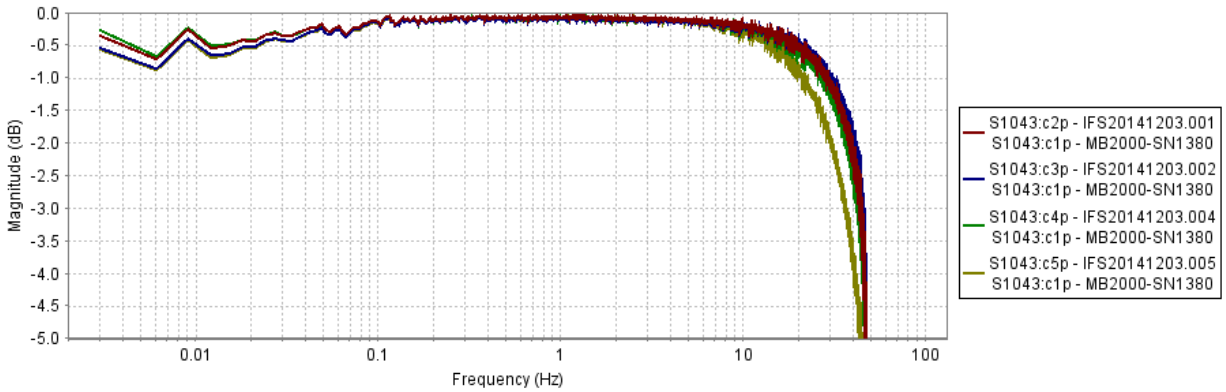

Figure 12 Piston-phone White Noise Relative Magnitude

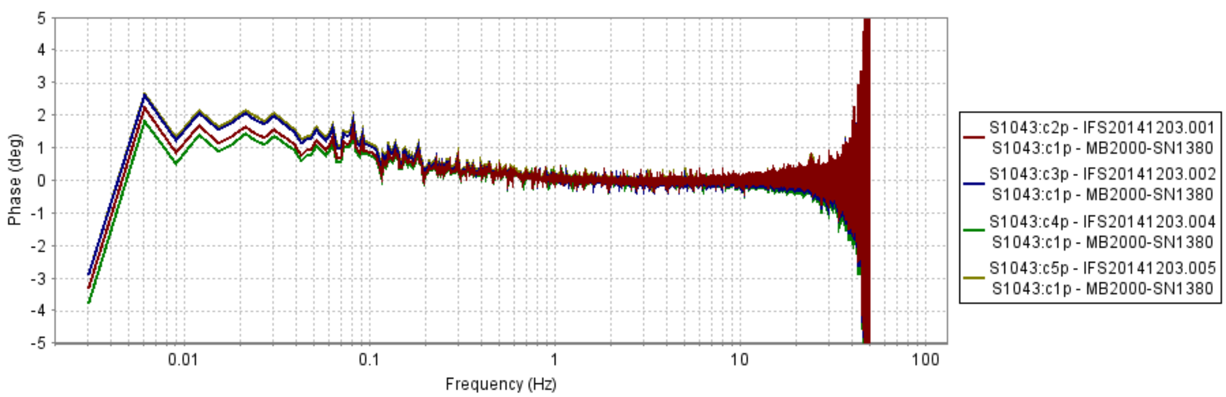

Figure 13 Piston-phone White Noise Relative Phase

Here we can see that the variation in magnitude and phase between the outputs of the MB2000 reference and each of the Hyperion 5113/GP sensors are described in the table below. There is sufficient coherence between the Hyperion 5113/GP and the MB2000 reference to be able to comment on the relative response over 0.01 to 30 Hz.

Table 13 Piston-phone White Noise Relative Magnitude and Phase, 0.01 – 30 Hz

	Magnitude	Phase
5113/GP 20141203.001	-0.08 dB / - 0.12 dB	+ 1.56 deg / + 0 deg
5113/GP 20141203.002	-0.11 dB / -0.15 dB	+ 1.94 deg / + 0 deg
5113/GP 20141203.004	-0.1 dB / -0.14 dB	+ 1.25 deg / + 0 deg
5113/GP 20141203.005	-0.1 dB / -0.15 dB	+ 2.03 deg / + 0 deg

The theoretical response models for the MB2000 and the Hyperion 5113/GP have a 3 dB low frequency corner at 0.01 Hz and 0.03 Hz, respectively, and then flat beyond that. Given the agreement between the response corrected relative magnitude and phase plots, the evaluated 5113/GP sensors are consistent with their theoretical response model in both magnitude and phase.

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 0.607 dB.

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

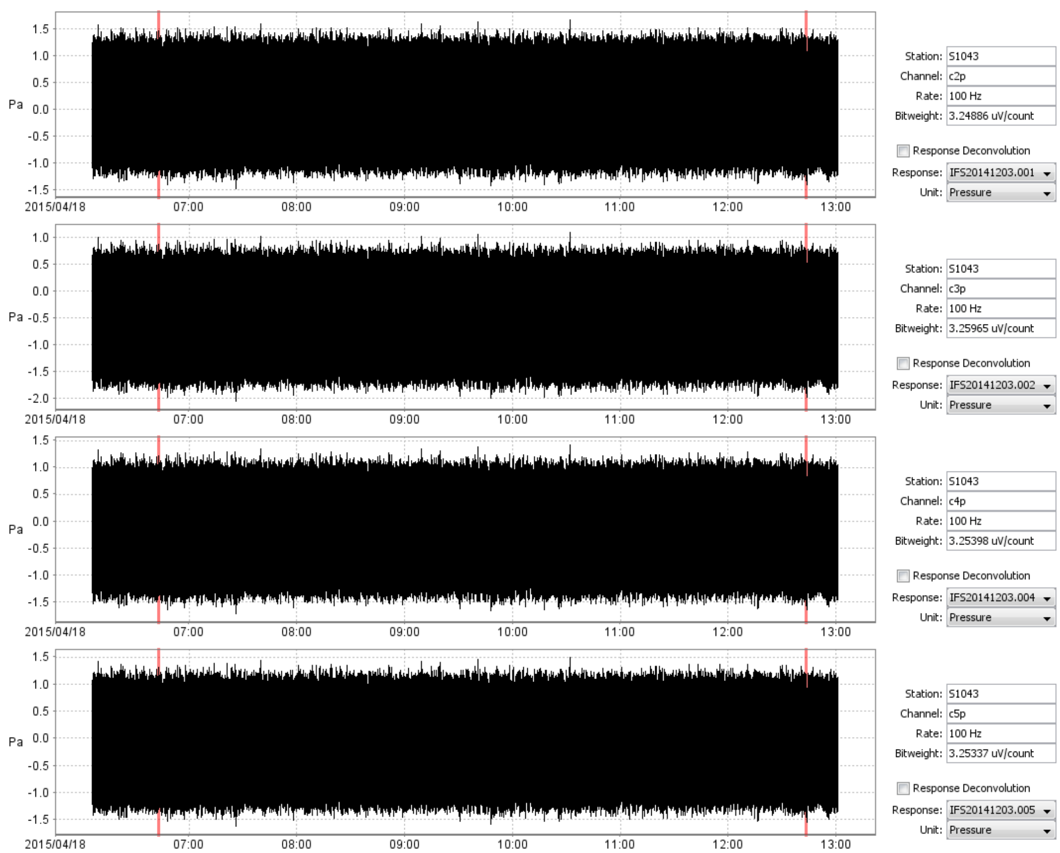

Figure 14 Hyperion 5113/GP Dynamic Noise Time Series

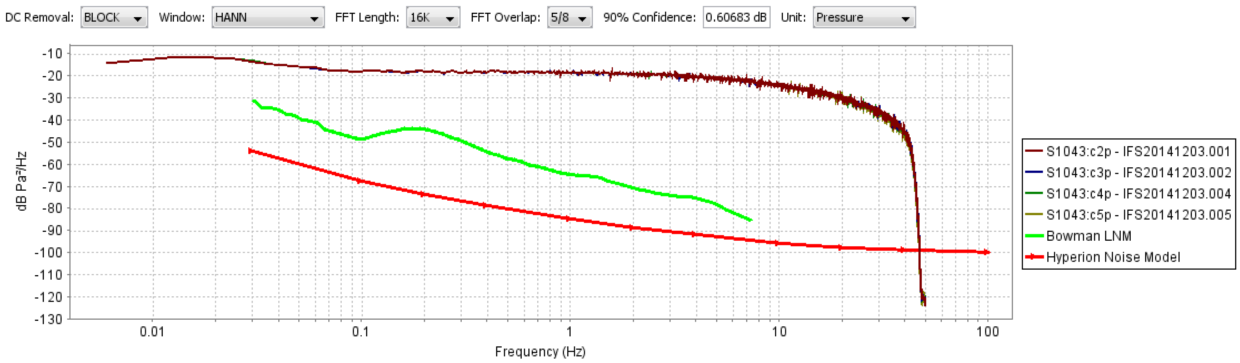

Figure 15 Hyperion 5113/GP Dynamic Noise Power Spectra

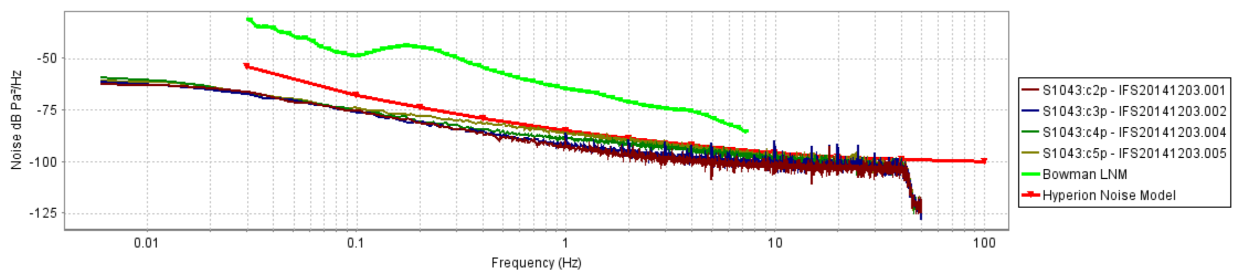

Figure 16 Hyperion 5113/GP Dynamic Noise Incoherent Noise

We observe that the 5113/GP self-noise, represented by the incoherent noise, is consistent with the 5113/GP noise model from Hyperion 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 5113/GP self-noise is below the Bowman LNM.

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.

A vehicle was then driven around the FACT site bunker for approximately 10 minutes to generate the desired ground motion. The time series and power spectra of the GS13, MB2000, and 5113/GP sensors are shown below.

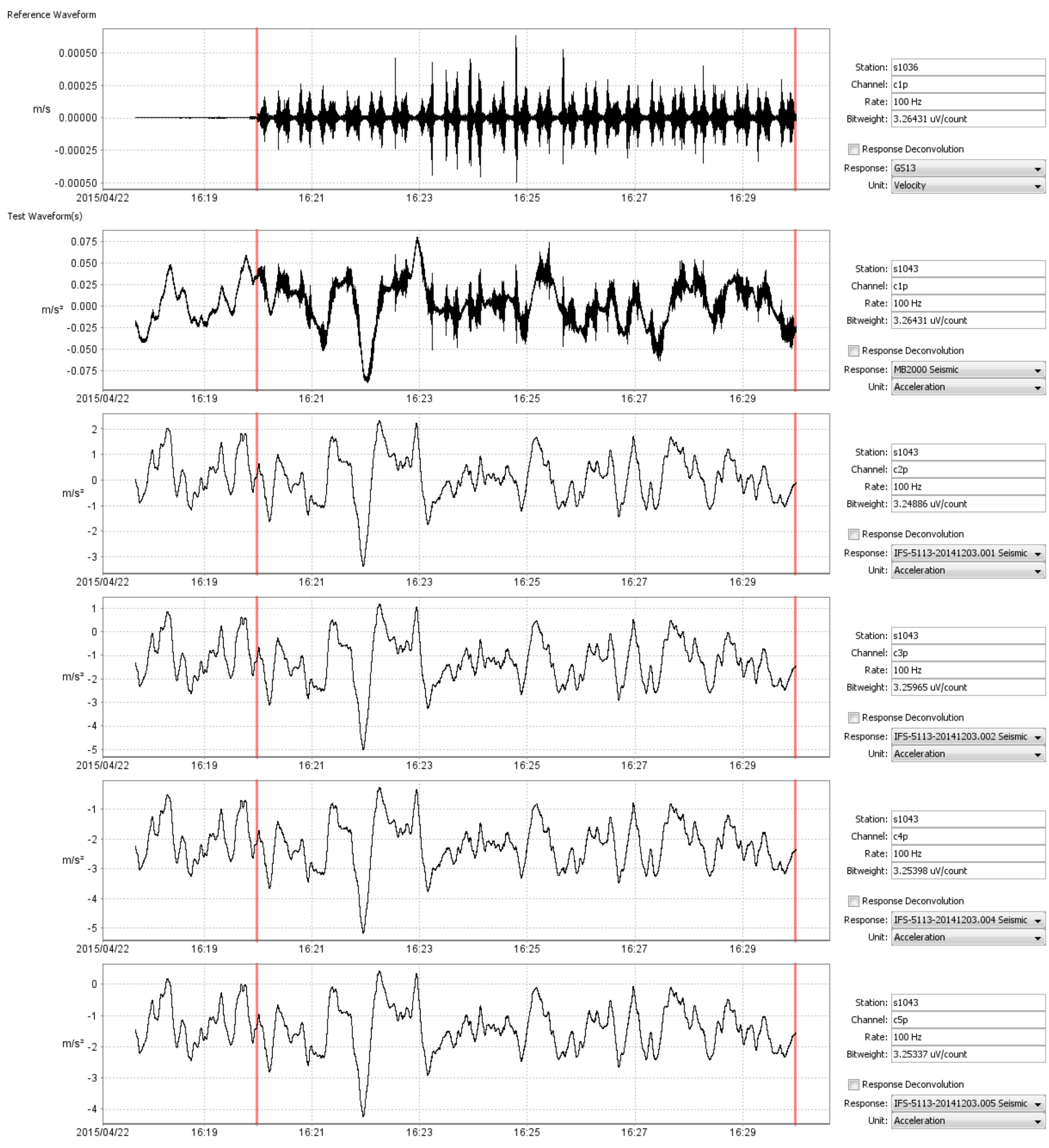

Figure 17 Seismic and Infrasound Time Series Due to Ground Motion

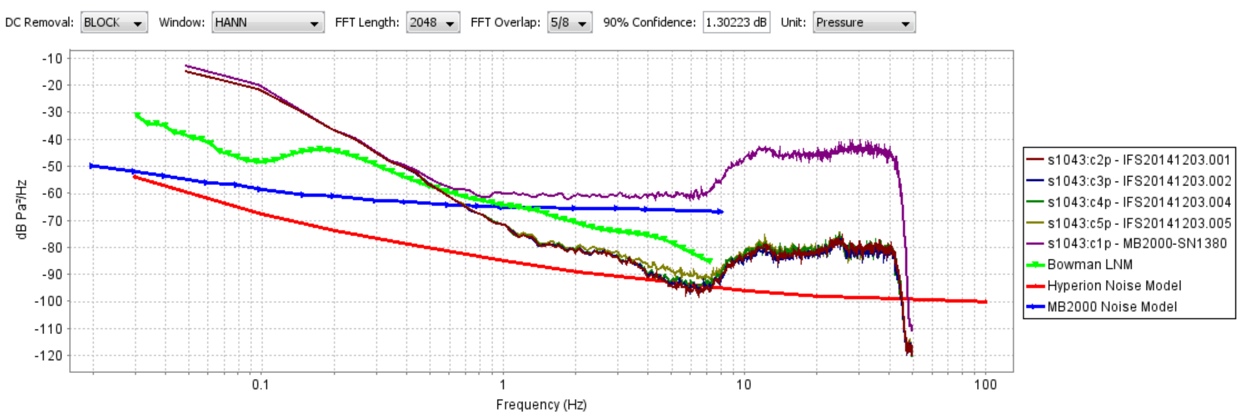

Figure 18 Pressure Power Spectra Due to Ground Motion

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 sensors at frequencies above 7 Hz when it becomes greater in magnitude than the respective sensor self-noise.

The seismic sensitivity of the 5113/GP 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, 512 FFT length and 7/8 window overlap. With the amount of data processed this provided a 90% confidence interval of 0.641 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.

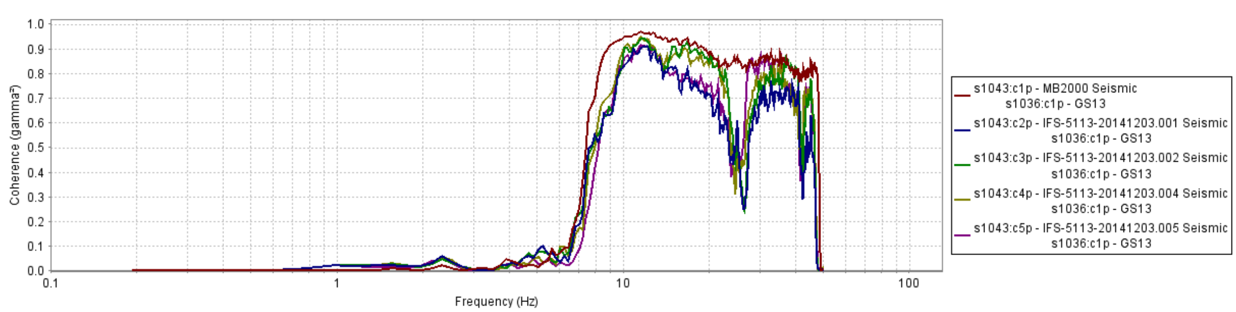

Figure 19 Seismic Ground Motion Coherence

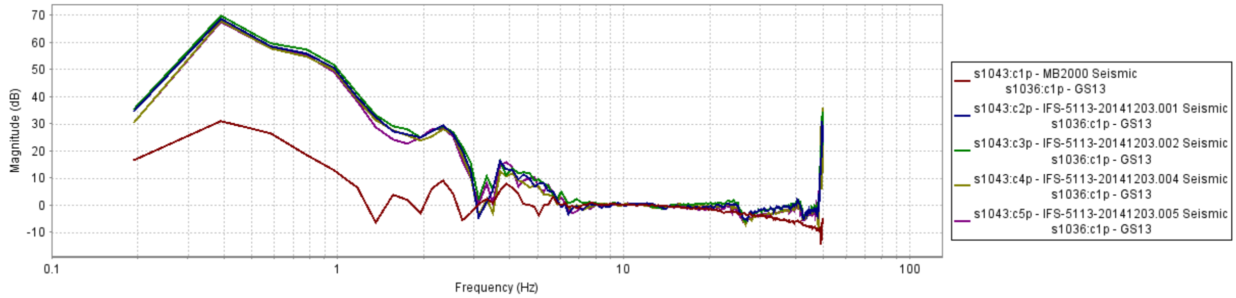

Figure 20 Ground Motion Magnitude Relative to the GS13 Seismometer

The identified seismic sensitivity values for the 5113/GP sensors are shown in the table below:

Table 14 Infrasound Sensor Seismic Sensitivity

Sensor	Seismic Sensitivity at 10 Hz	Seismic Pressure Sensitivity at 10 Hz
IFS5113/GP 20141203.001	8.33 mV/(m/s^2)	0.083 Pa/(m/s^2)
IFS5113/GP 20141203.002	7.60 mV/(m/s^2)	0.076 Pa/(m/s^2)
IFS5113/GP 20141203.004	9.70 mV/(m/s^2)	0.097 Pa/(m/s^2)
IFS5113/GP 20141203.005	10.1 mV/(m/s^2)	0.101 Pa/(m/s^2)

The 5113/GP specifications state that the seismic sensitivity is less than 0.08 Pa/m/s^2. Using the 5113/GP's nominal sensitivity of 100 mV/Pa, the seismic sensitivity specification is equivalent to 8 mV/(m/s^2). We observed seismic sensitivities of between 0.076 and 0.101 Pa/(m/s^2), a difference of -5% (0.45 dB) and +26% (2 dB), respectively.

For comparison, the following plot of power spectra in ground acceleration of the seismic sensitivity data from the GS13 Seismometer and the infrasound sensors scaled by their seismic sensitivity responses.

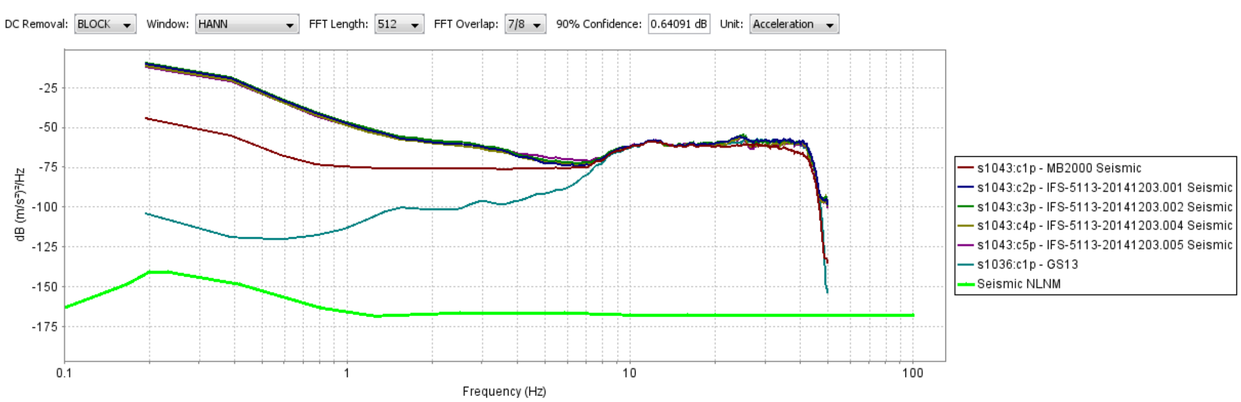

Figure 21 Ground Motion Power Spectra

This plot of ground motion is illustrative of the levels of ground acceleration needed to be visible on the output of the 5113/GP in a quiet pressure environment. The power spectra show the ground acceleration equivalent of the sensor output.

4 EVALUATION SUMMARY

Power:
The observed power consumption of the Hyperion 5113/GP was between approximately 1.41 and 1.56 W at 13.1 V. The stated power consumption from the sensor specifications was 1.5 W.

Isolation Noise:
The observed self-noise of the 5113/GP sensors were entirely below the Bowman LNM across its 0.03 to 7 Hz passband. The measured sensor self-noise was consistent with the noise model provided by Hyperion.

Dynamic Range:
The observed dynamic range of the 5113/GP sensors was more than 111 dB over 0.01 – 40 Hz and over 114 dB over 0.02 – 4 Hz.

Frequency Amplitude Response Verification:
The observed sensitivity at 1 Hz of the Hyperion 5113/GP sensors were all between 1.0% 0.04 dB) and 1.3% (0.06 dB) of their provided datasheet sensitivities of approximately 100 mV/Pa The sensitivities were consistent across a range of amplitudes, from approximately 0.1345 Pa to 4.695 Pa, differing by less than 0.05 % (0.002 dB) across amplitude. All observed variations in sensitivity across a frequency range of 0.02 to 10 Hz were consistent with the 5113/GP response model provided by Hyperion.

Frequency Amplitude Phase Verification:
Broadband measurements of a white noise source indicate that both the Hyperion 5113/GP sensors have a response that is flat across 0.01 to 30 Hz to within 0.15 dB in magnitude and 2 degrees in phase. All of the Hyperion 5113/GP sensors were consistent in their magnitude and phase response except for serial # 20141203.005 whose magnitude response appears to roll off slightly faster than the other above 10 Hz.

Dynamic Noise:
The observed self-noises of the 5113/GP sensors, while measuring amplitudes as much as 70 dB above its noise model, were consistent with its noise model.

Seismic Sensitivity:
The 5113/GP sensors have a measured sensitivity to ground motion of between 7.6 and 10.1 mV/(m/s^2) at 10 Hz. This range is slightly above the specification of 8 mV/(m/s^2).

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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.

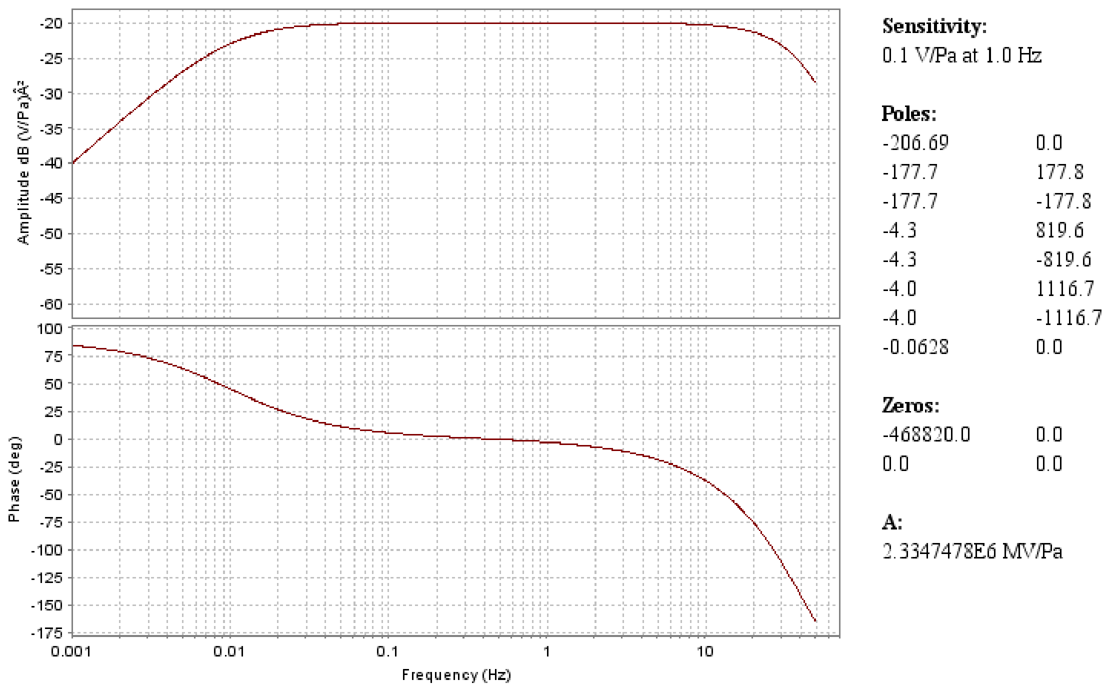

Figure 22 MB2000 Response

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.

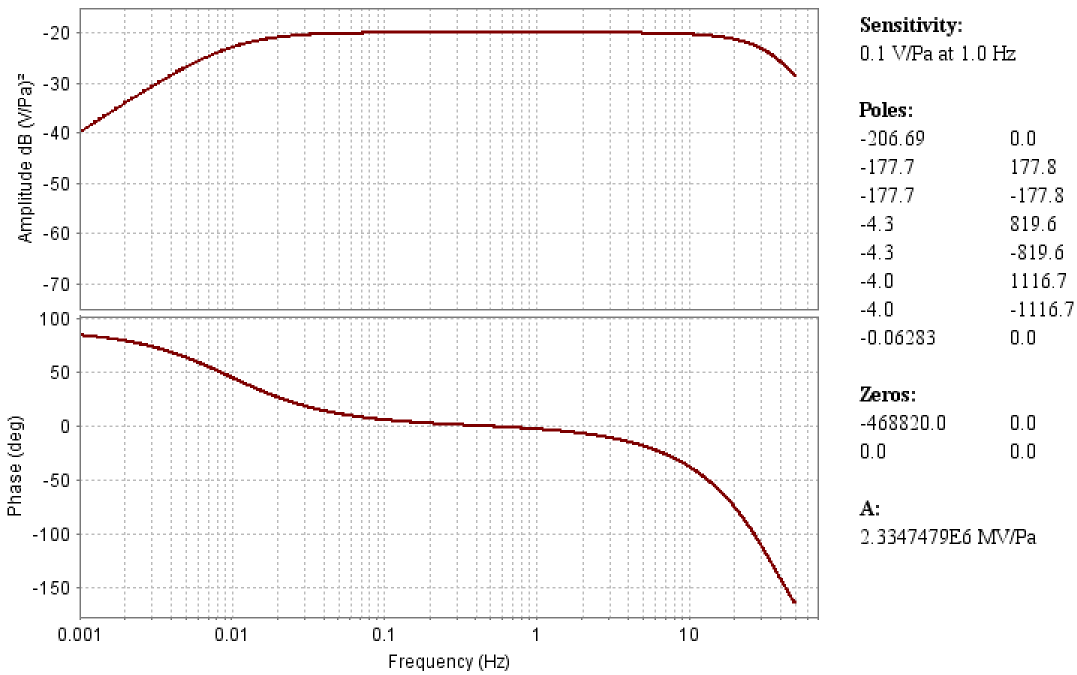

Figure 23 MB2005 Response

Hyperion 5113/GP Response

The 5113/GP responses were provided to SNL by Hyperion with the sensitivity, poles, and zeros below.

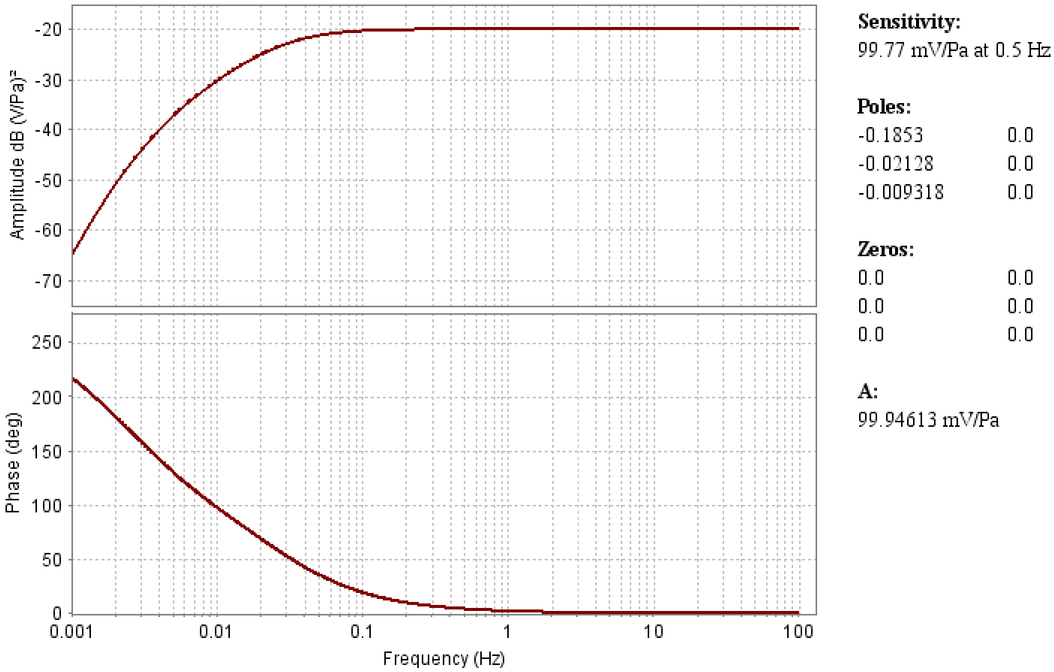

Figure 24 Hyperion 5113/GP #20141203.001 Response

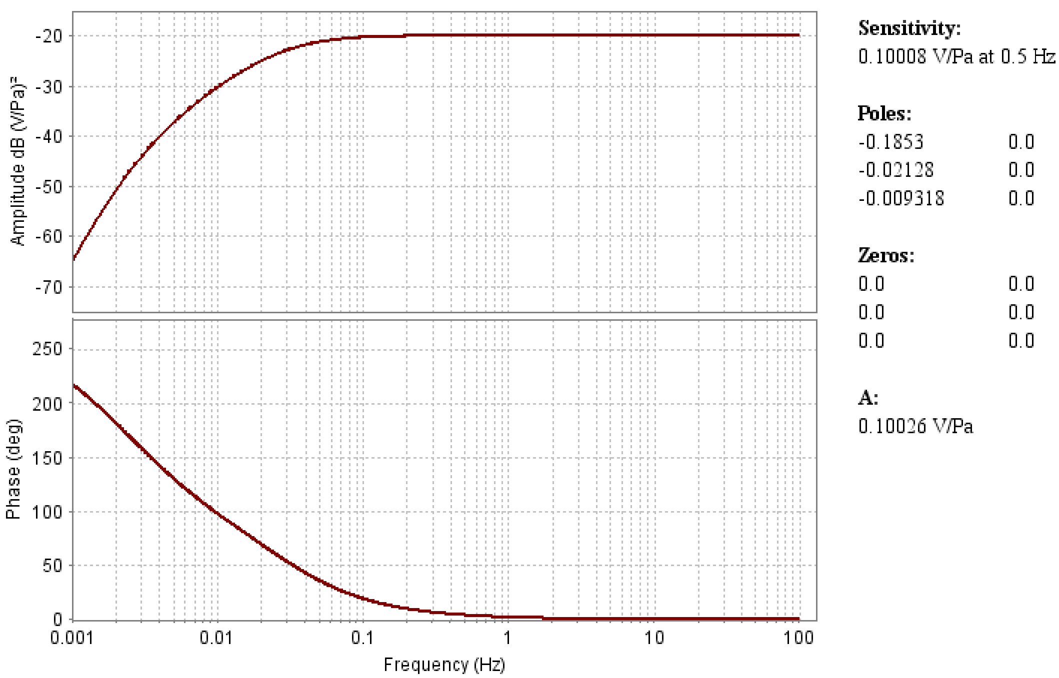

Figure 25 Hyperion 5113/GP #20141203.002 Response

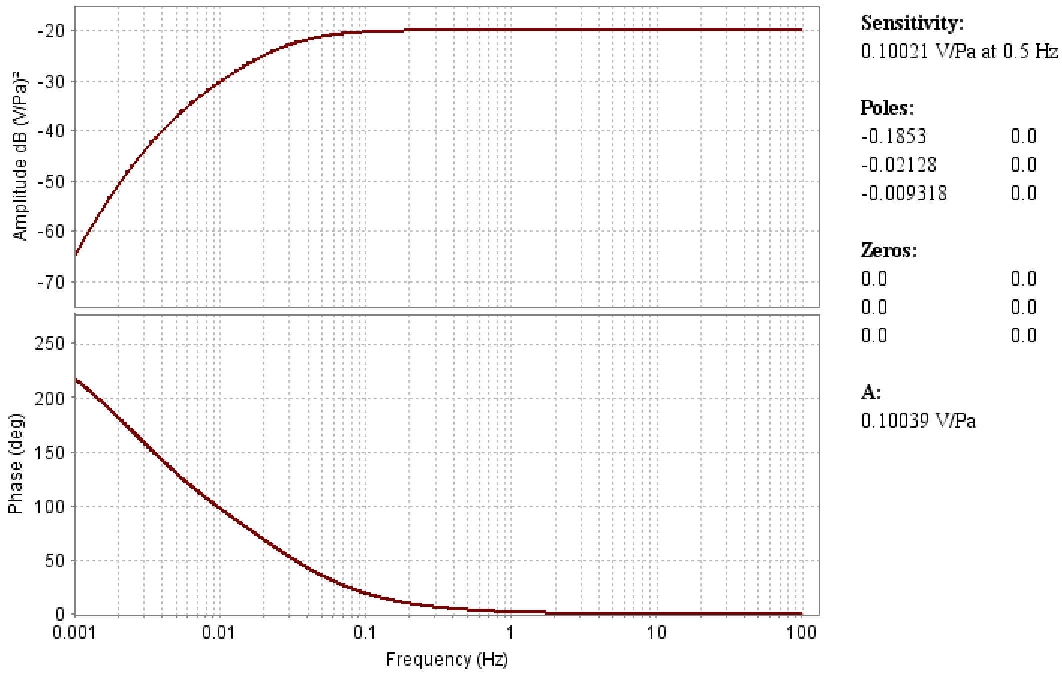

Figure 26 Hyperion 5113/GP #20141203.004 Response

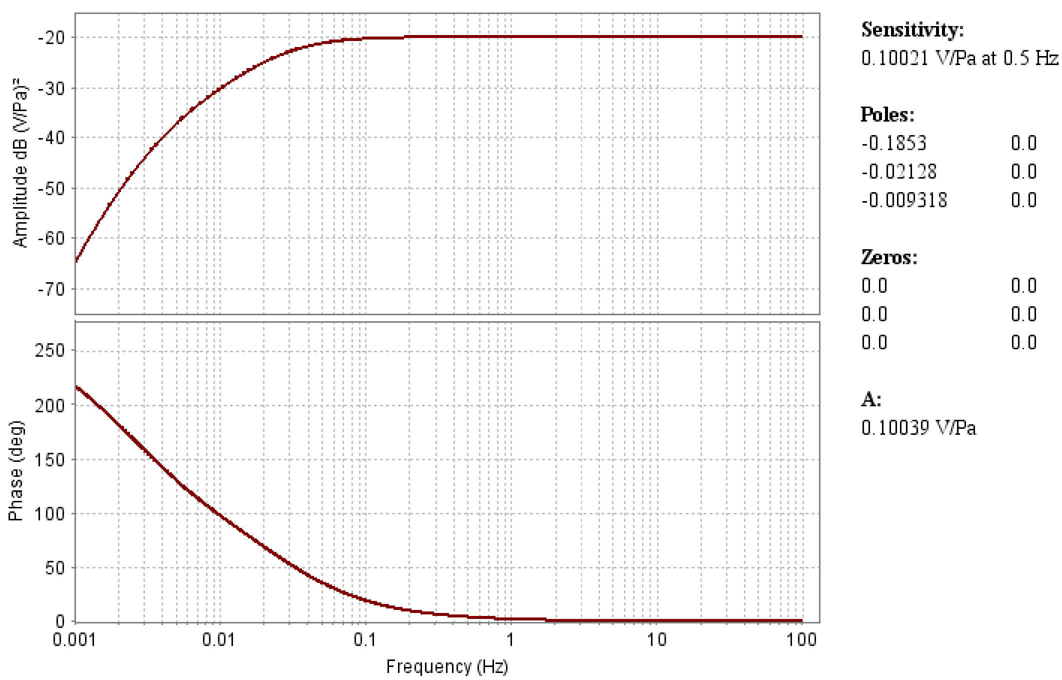

Figure 27 Hyperion 5113/GP #20141203.005 Response

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