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Hyperion 5113/A Infrasound Sensor Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated an infrasound sensor, the 5113/A 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, and dynamic range. The 5113/A infrasound sensor is a new revision of the 5000 series intended to meet the infrasound application requirements for 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 Energy Office of Nuclear Verification (NA-221). The sensors under test were purchased by Sandia National Laboratories from Hyperion and are the property of the U.S. Government.

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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/A Infrasound Sensors

The evaluation of 3 Hyperion 5113/A infrasound sensors, serial numbers 20150305.001, 20150305.002, and 20150305.003 was performed by Sandia National Laboratories (SNL). The Hyperion 5113/A 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, and dynamic range compared against the manufacturer's specifications and monitoring requirements. The 5113/A infrasound sensor is a new revision of the 5000 series intended to meet the infrasound application requirements for use in the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

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

Characteristics	Minimum Requirements	Hyperion 5113/A
Sensor Type	Microbarometer	Microbarometer
Number of sensors	4-element array[1]	
Geometry	Triangle with a component at the centre	
Spacing	Triangle basis: 1 to 3 km[2]	
Station location accuracy	≤100m	
Relative sensor location	≤1 m	
Measured parameter	Absolute[3] or differential pressure	Differential pressure
Passband	0.02 to 4 Hz	0.0088 to 100 Hz (evaluated to 30 Hz)
Sensor response	Flat to pressure over the passband	Flat to within 3 dB
Sensor noise	≤ 18 dB below minimum acoustic noise[4]	44 dB below minimum acoustic noise
Calibration	≤5% in absolute amplitude[5]	< 1.6% deviation from manufacturer's datasheet
State of health	Status data transmitted to the International Data Center	
Sampling rate	≥ 10 samples per second	
Resolution	≥ 1 count per 1 mPa	58.7 counts/mPa (140 mV/Pa with a 40 Vpp 24-bit digitizer)
Dynamic range	≥ 108 dB	> 115 dB
Timing Accuracy	≤1 ms[6]	
Standard temperature range	-10°C to +45°C[7]	Evaluated at approximately 20°C
Buffer at station or at National Data Center	≥7 days	
Data format	Group of Scientific Expert format	
Data frame length	≤30 seconds	
Data transmission	Continuous	
Data availability	≥98 %	
Timely data availability	≥97 %	
Mission-capable array	≥3 elements operational	
Acoustic filtering	Noise reduction pipes (site dependent)	
Auxiliary data	Meteorological data[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 5113/A infrasound sensor. Notable features of the 5113/A include seismically decoupled transducer and an expanded frequency pass-band. Basic infrasound sensor characterization includes determining sensitivity, linearity to pressure input, power, self-noise, full-scale, dynamic range, 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/A sensors was performed on April 22-28, 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)

2.5 Test Configuration and System Specifications

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

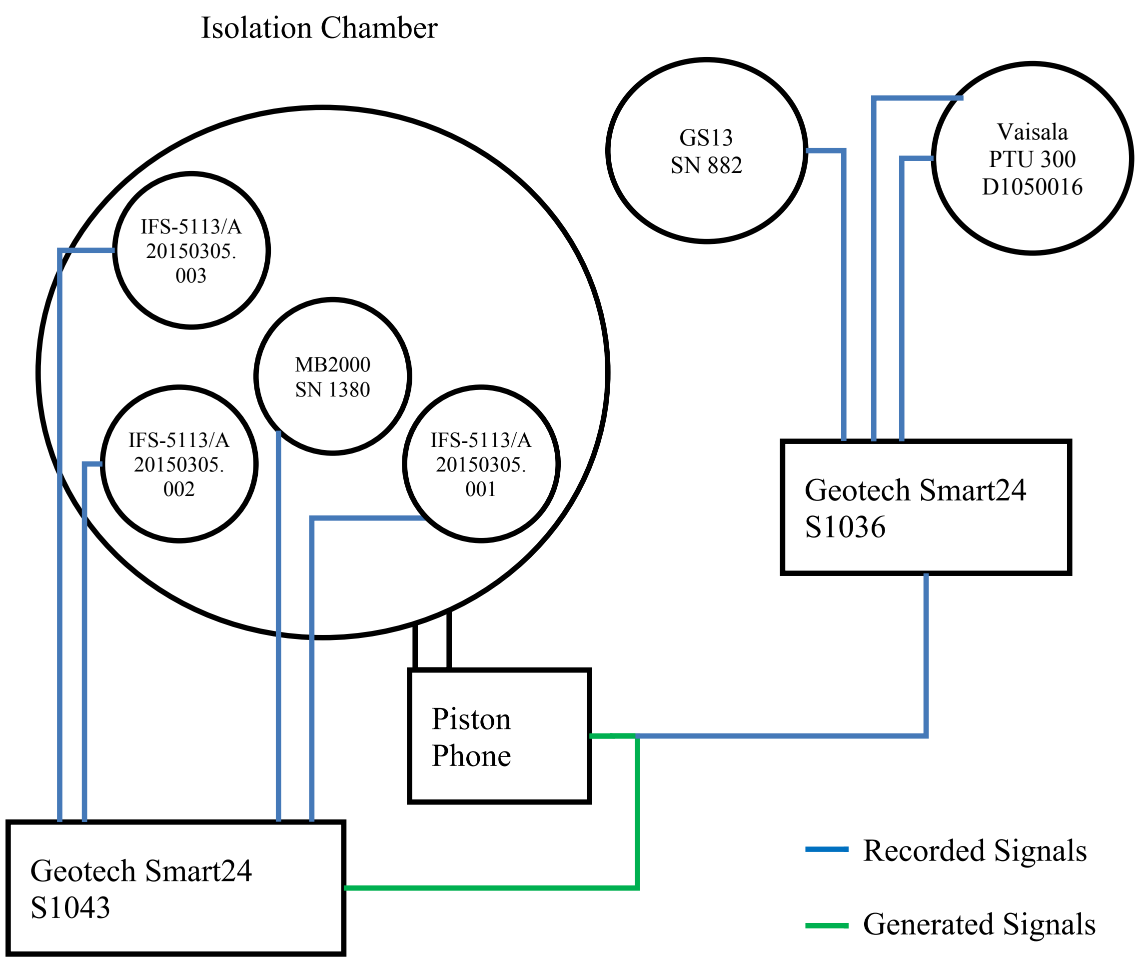

Figure 2 Test Configuration Diagram

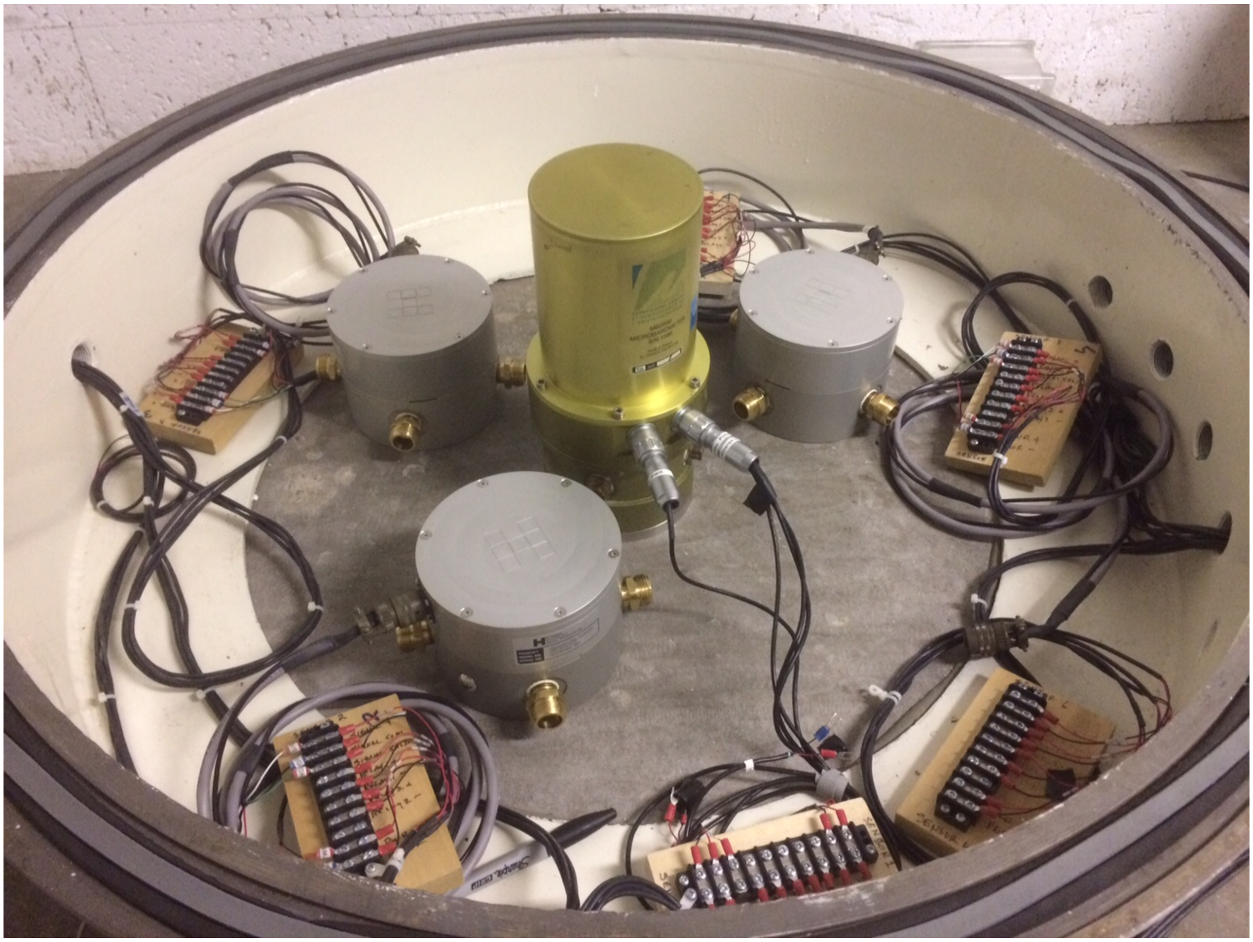

Figure 3 Isolation Chamber, MB2000 Reference, Hyperion 5113/A Sensors

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 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/A 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 2 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 3 Geotech Smart24 Digitizer S1043 Configuration

Channel Name	Bitweight	Description
c1p / c1s	3.26431 uV/count	MB2000 SN1380
c2p / c2s	3.24886 uV/count	IFS-5113A 20150305.001
c3p / c3s	3.25965 uV/count	IFS-5113A 20150305.002
c4p / c4s	3.25398 uV/count	IFS-5113A 20150305.003

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/A 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.

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/A 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. 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 and 16 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/A 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 Hyperion 5113/A Power Consumption

Sensor	Power Supply Voltage	Current	Power Consumption
IFS-5113/A 20150305.001	13.26 V	120.8 mA	1.602 W
IFS-5113/A 20150305.001	13.24 V	106.3 mA	1.407 W
IFS-5113/A 20150305.001	13.24 V	120.1 mA	1.590 W

The observed power consumption of the Hyperion 5113/A was between 1.407 W and 1.602 W at 13.24 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.

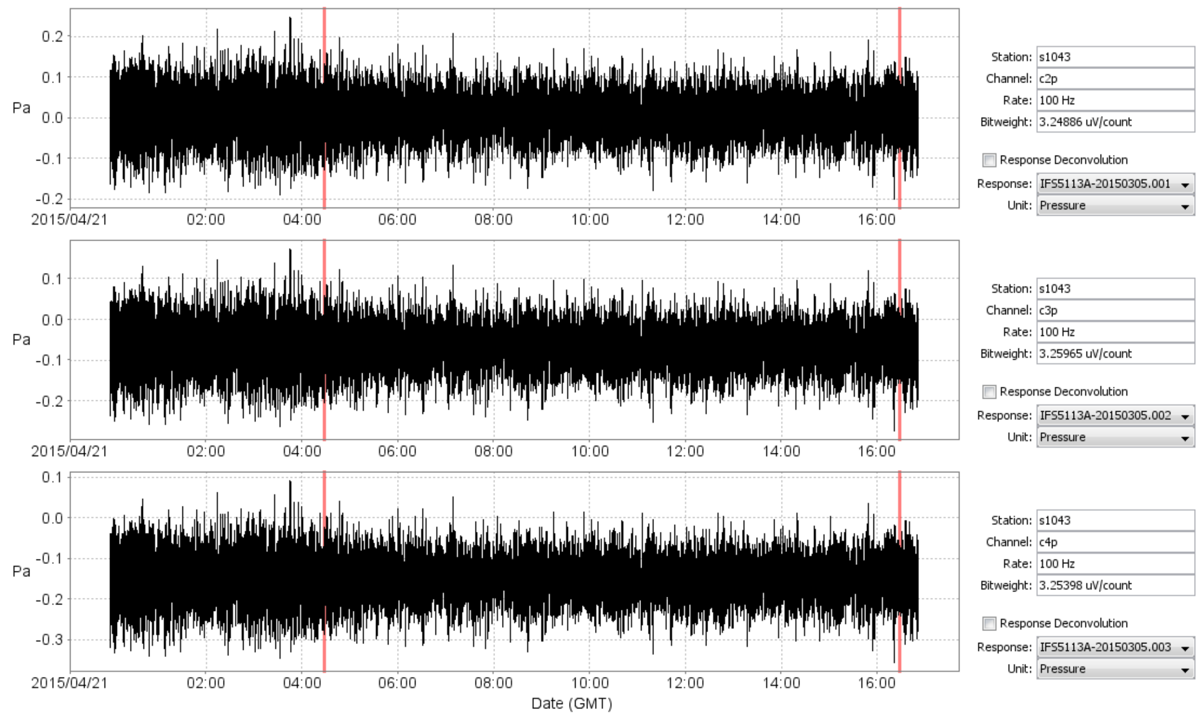

Figure 5 Hyperion 5113/A Isolation Time Series

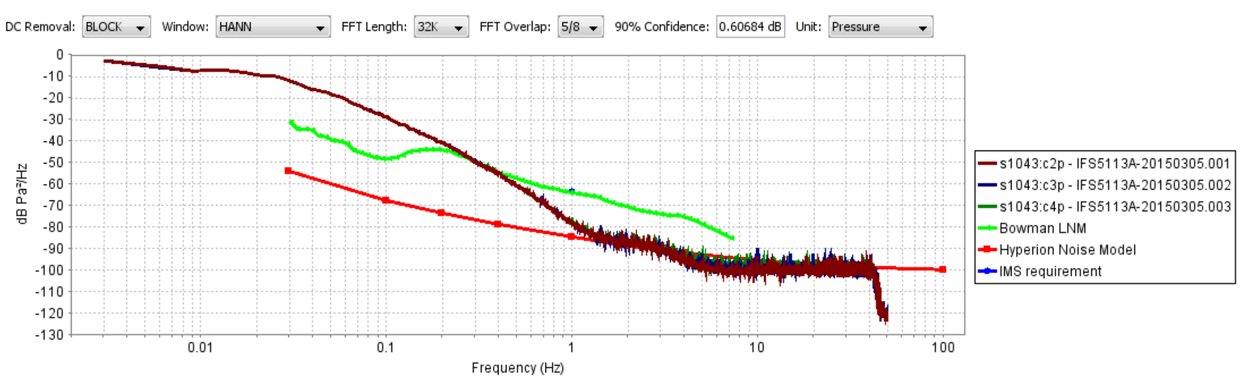

Figure 6 Hyperion 5113/A Isolation Power Spectra

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

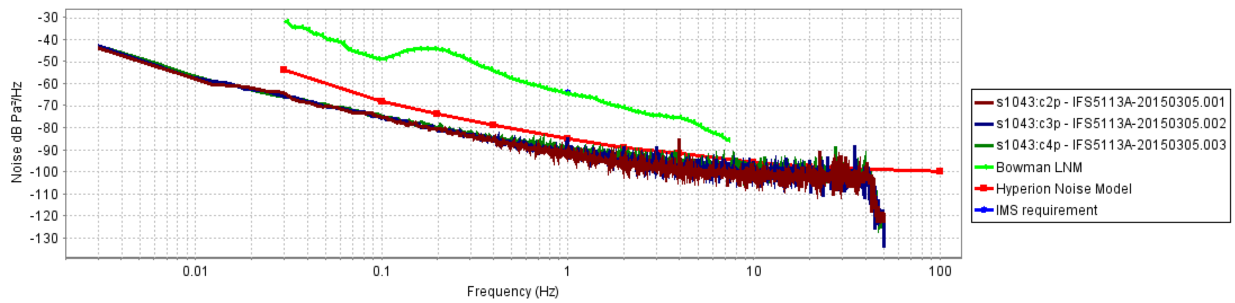

Figure 7 Hyperion 5113/A Isolation Incoherent Self-Noise

As may be seen, the evaluated 5113/A self-noise is consistent with the noise model provided by Hyperion. In addition, the 5113/A self-noise is entirely below the Bowman LNM across its defined frequency range of 0.03 to 7 Hz. At 1 Hz, all evaluated Hyperion 5113/A infrasound sensors are more than 26 dB below the IMS requirement of being more than 18 dB below the minimum noise level of 5 mPa at 1 Hz. This corresponds to the 5113/A being 44 dB below the minimum noise level of 5 mPa at 1 Hz

The calculated RMS noise values from the self-noise power spectra are shown in the table below.

Table 5 Hyperion 5113/A RMS Noise

Waveform	8.8 mHz - 40 Hz	20 mHz - 4 Hz
s1043:c2p - IFS5113A-20150305.001	0.17228 mPa rms	0.1182 mPa rms
s1043:c3p - IFS5113A-20150305.002	0.17856 mPa rms	0.12036 mPa rms
s1043:c4p - IFS5113A-20150305.003	0.18978 mPa rms	0.12397 mPa rms

3.3 Dynamic Range

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

Using the sensor self-noise estimate obtained from 3.2 Isolation Noise, which is believed to be the best estimate of self-noise available, the RMS noise and dynamic range using the 5113/A 14 V clip level at 1 Hz are:

Table 6 Hyperion 5113/A Dynamic Range

Waveform	8.8 mHz - 40 Hz	20 mHz - 4 Hz
s1043:c2p - IFS5113A-20150305.001	112.24 dB	115.51 dB
s1043:c3p - IFS5113A-20150305.002	111.97 dB	115.39 dB
s1043:c4p - IFS5113A-20150305.003	111.36 dB	115.06 dB

Using the low-end specification of the Hyperion 5113/A of 8.8 mHz to the high end frequency of 40 Hz that was collected, the sensors exhibited between 111.36 and 112.24 dB of dynamic range. Over the IMS pass-band of 0.02 – 4 Hz, the sensor exhibited between 115.06 and 115.51 dB of dynamic range, which exceeds the IMS requirement of 108 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 7 Piston-phone Tone Amplitudes

Amplitudes (Volts) into piston-phone	Approximate pressure (at 1 Hz) within the chamber
0.01 V	0.01311 Pa
0.05 V	0.006646 Pa
0.1 V	0.1338 Pa
0.5 V	0.7174 Pa
1 V	1.544 Pa
2 V	3.312 Pa
3 V	4.653 Pa

Table 8 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

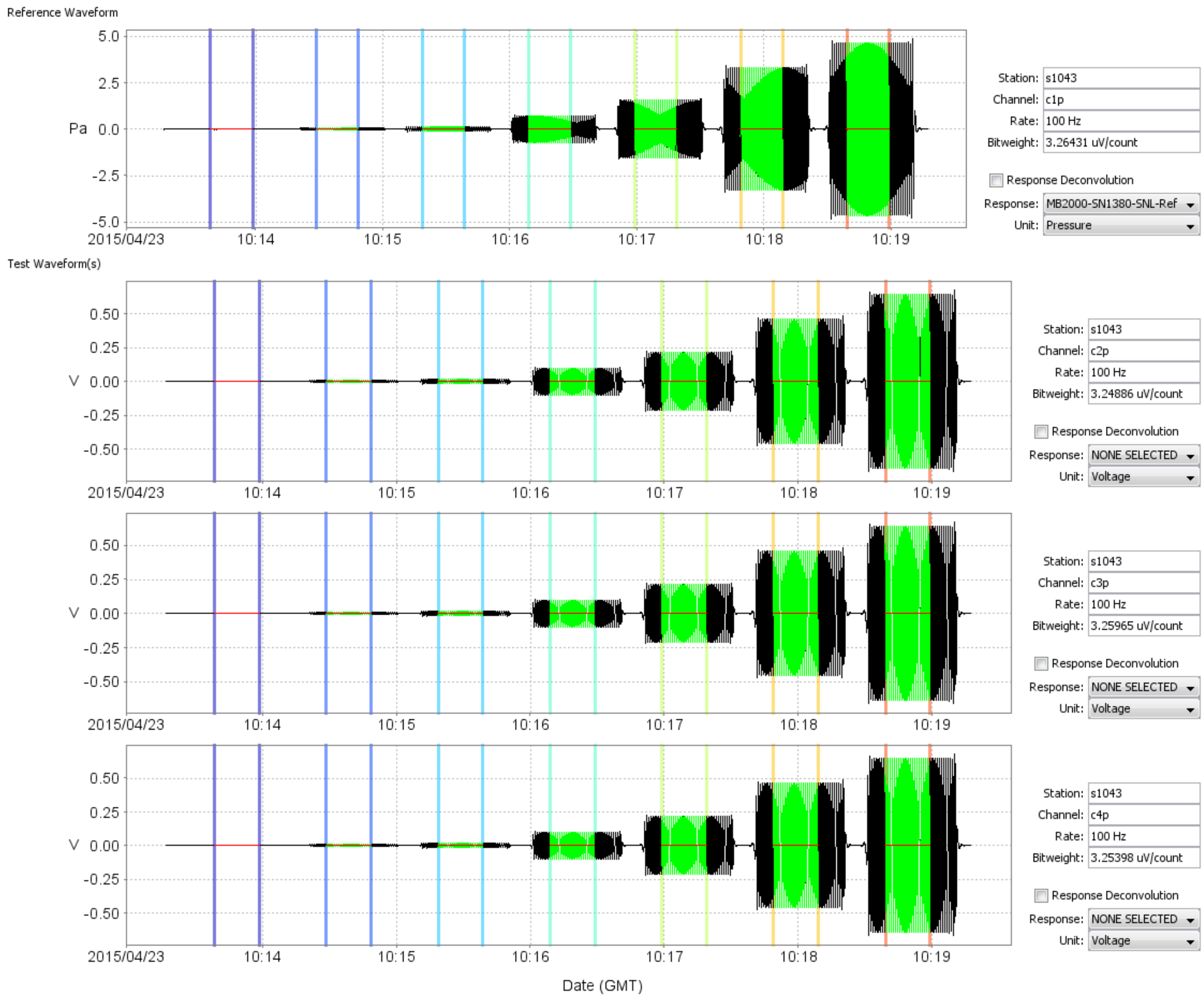

Figure 8 Piston-phone Tone Time Series for 1 Hz

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 9 Piston-phone Sensitivities for 5113/A 20150305.001

Pressure (at 1 Hz)	Theoretical (140.42 mV/Pa @ 0.5 Hz)	0.01311 Pa	0.006646 Pa	0.1338 Pa	0.7174 Pa	1.544 Pa	3.312 Pa	4.653 Pa
0.02 Hz	0.1126 V/Pa	*	*	*	0.1096 V/Pa	0.1098 V/Pa	0.1097 V/Pa	0.1097 V/Pa
0.04 Hz	0.1317 V/Pa	*	*	*	0.1330 V/Pa	0.1330 V/Pa	0.1330 V/Pa	0.1330 V/Pa
0.08 Hz	0.1381 V/Pa	*	*	0.1372 V/Pa	0.1370 V/Pa	0.1371 V/Pa	0.1370 V/Pa	0.1370 V/Pa
0.1 Hz	0.1390 V/Pa	*	*	0.1378 V/Pa	0.1377 V/Pa	0.1376 V/Pa	0.1376 V/Pa	0.1376 V/Pa
0.2 Hz	0.1401 V/Pa	*	0.1389 V/Pa	0.1383 V/Pa	0.1385 V/Pa	0.1385 V/Pa	0.1385 V/Pa	0.1385 V/Pa
0.4 Hz	0.1404 V/Pa	0.1386 V/Pa	0.1387 V/Pa	0.1386 V/Pa	0.1387 V/Pa	0.1387 V/Pa	0.1387 V/Pa	0.1387 V/Pa
0.8 Hz	0.1405 V/Pa	0.1401 V/Pa	0.1389 V/Pa	0.1388 V/Pa	0.1388 V/Pa	0.1388 V/Pa	0.1388 V/Pa	0.1388 V/Pa
1 Hz	0.1405 V/Pa	0.1382 V/Pa	0.1376 V/Pa	0.1382 V/Pa	0.1387 V/Pa	0.1387 V/Pa	0.1387 V/Pa	0.1387 V/Pa
2 Hz	0.1405 V/Pa	0.1384 V/Pa	0.1377 V/Pa	0.1385 V/Pa	0.1386 V/Pa	0.1386 V/Pa	0.1387 V/Pa	0.1387 V/Pa
4 Hz	0.1405 V/Pa	0.1378 V/Pa	0.1361 V/Pa	0.1380 V/Pa	0.1388 V/Pa	0.1389 V/Pa	0.1389 V/Pa	0.1389 V/Pa
8 Hz	0.1405 V/Pa	0.1445 V/Pa	0.1390 V/Pa	0.1415 V/Pa	0.1404 V/Pa	0.1404 V/Pa	0.1404 V/Pa	0.1404 V/Pa
10 Hz	0.1405 V/Pa	*	0.1364 V/Pa	0.1356 V/Pa	0.1368 V/Pa	0.1365 V/Pa	0.1364 V/Pa	0.1364 V/Pa

Table 10 Piston-phone Sensitivities for 5113/A 20150305.002

Pressure (at 1 Hz)	Theoretical (139.82 mV/Pa @ 0.5 Hz)	0.01311 Pa	0.006646 Pa	0.1338 Pa	0.7174 Pa	1.544 Pa	3.312 Pa	4.653 Pa
0.02 Hz	0.1121 V/Pa	*	*	*	0.1077 V/Pa	0.1079 V/Pa	0.1077 V/Pa	0.1078 V/Pa
0.04 Hz	0.1311 V/Pa	*	*	*	0.1316 V/Pa	0.1316 V/Pa	0.1316 V/Pa	0.1316 V/Pa
0.08 Hz	0.1375 V/Pa	*	*	0.1360 V/Pa	0.1359 V/Pa	0.1360 V/Pa	0.1359 V/Pa	0.1359 V/Pa
0.1 Hz	0.1384 V/Pa	*	*	0.1368 V/Pa	0.1366 V/Pa	0.1365 V/Pa	0.1366 V/Pa	0.1365 V/Pa
0.2 Hz	0.1395 V/Pa	*	0.1379 V/Pa	0.1374 V/Pa	0.1375 V/Pa	0.1375 V/Pa	0.1375 V/Pa	0.1375 V/Pa
0.4 Hz	0.1398 V/Pa	0.1379 V/Pa	0.1377 V/Pa	0.1377 V/Pa	0.1378 V/Pa	0.1377 V/Pa	0.1378 V/Pa	0.1378 V/Pa
0.8 Hz	0.1399 V/Pa	0.1392 V/Pa	0.1379 V/Pa	0.1379 V/Pa	0.1378 V/Pa	0.1378 V/Pa	0.1378 V/Pa	0.1378 V/Pa
1 Hz	0.1399 V/Pa	0.1373 V/Pa	0.1367 V/Pa	0.1373 V/Pa	0.1378 V/Pa	0.1378 V/Pa	0.1378 V/Pa	0.1378 V/Pa
2 Hz	0.1399 V/Pa	0.1376 V/Pa	0.1368 V/Pa	0.1376 V/Pa	0.1377 V/Pa	0.1377 V/Pa	0.1378 V/Pa	0.1378 V/Pa
4 Hz	0.1399 V/Pa	0.1369 V/Pa	0.1353 V/Pa	0.1372 V/Pa	0.1380 V/Pa	0.1381 V/Pa	0.1380 V/Pa	0.1380 V/Pa
8 Hz	0.1399 V/Pa	0.1440 V/Pa	0.1385 V/Pa	0.1409 V/Pa	0.1399 V/Pa	0.1398 V/Pa	0.1398 V/Pa	0.1398 V/Pa
10 Hz	0.1399 V/Pa	*	0.1360 V/Pa	0.1353 V/Pa	0.1364 V/Pa	0.1361 V/Pa	0.1360 V/Pa	0.1360 V/Pa

Table 11 Piston-phone Sensitivities for 5113/A 20150305.003

Pressure (at 1 Hz)	Theoretical (141.05 mV/Pa @ 0.5 Hz)	0.01311 Pa	0.006646 Pa	0.1338 Pa	0.7174 Pa	1.544 Pa	3.312 Pa	4.653 Pa
0.02 Hz	0.1131 V/Pa	*	*	*	0.1093 V/Pa	0.1094 V/Pa	0.1093 V/Pa	0.1094 V/Pa
0.04 Hz	0.1323 V/Pa	*	*	*	0.1331 V/Pa	0.1332 V/Pa	0.1332 V/Pa	0.1332 V/Pa
0.08 Hz	0.1387 V/Pa	*	*	0.1375 V/Pa	0.1374 V/Pa	0.1375 V/Pa	0.1374 V/Pa	0.1374 V/Pa
0.1 Hz	0.1396 V/Pa	*	*	0.1383 V/Pa	0.1381 V/Pa	0.1380 V/Pa	0.1381 V/Pa	0.1381 V/Pa
0.2 Hz	0.1407 V/Pa	*	0.1394 V/Pa	0.1389 V/Pa	0.1390 V/Pa	0.1390 V/Pa	0.1390 V/Pa	0.1390 V/Pa
0.4 Hz	0.1410 V/Pa	0.1392 V/Pa	0.1392 V/Pa	0.1392 V/Pa	0.1393 V/Pa	0.1392 V/Pa	0.1393 V/Pa	0.1393 V/Pa
0.8 Hz	0.1411 V/Pa	0.1407 V/Pa	0.1394 V/Pa	0.1394 V/Pa	0.1394 V/Pa	0.1393 V/Pa	0.1393 V/Pa	0.1393 V/Pa
1 Hz	0.1411 V/Pa	0.1389 V/Pa	0.1382 V/Pa	0.1388 V/Pa	0.1393 V/Pa	0.1393 V/Pa	0.1393 V/Pa	0.1393 V/Pa
2 Hz	0.1411 V/Pa	0.1391 V/Pa	0.1383 V/Pa	0.1391 V/Pa	0.1392 V/Pa	0.1392 V/Pa	0.1392 V/Pa	0.1393 V/Pa
4 Hz	0.1411 V/Pa	0.1384 V/Pa	0.1367 V/Pa	0.1386 V/Pa	0.1394 V/Pa	0.1395 V/Pa	0.1395 V/Pa	0.1395 V/Pa
8 Hz	0.1411 V/Pa	0.1453 V/Pa	0.1396 V/Pa	0.1420 V/Pa	0.1410 V/Pa	0.1409 V/Pa	0.1410 V/Pa	0.1410 V/Pa
10 Hz	0.1411 V/Pa	*	0.1369 V/Pa	0.1362 V/Pa	0.1373 V/Pa	0.1370 V/Pa	0.1369 V/Pa	0.1369 V/Pa

* There was insufficient signal to noise ratio on the sinusoid to estimate sensitivity.

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 0.01311 Pa – 4.653 Pa)
5113/A 20150305.001	0.1386 V/Pa	1.35% (0.058 dB)	0.29% (0.013 dB)
5113/A 20150305.002	0.1377 V/Pa	1.59% (0.069 dB)	0.29% (0.013 dB)
5113/A 20150305.003	0.1393 V/Pa	1.30% (0.056 dB)	0.01% (0.001 dB)

The sensitivities of the 5113/A sensors were observed to be between 0.1377 and 0.1393 V/Pa. The observed sensitivity values differed from each sensors nominal sensitivity on the manufacturer's calibration sheet by between 1.3% and 1.59%. All sensors were flat across the 0.1345 – 4.695 Pa amplitude range to within +/- 0.29% (0.013 dB). The variation in sensitivity observed across frequency was consistent with the magnitude response roll off provided by the manufacturer with a 3 dB corner frequency of 8.8 mHz.

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 six 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, 32K FFT length and 5/8 window overlap. With the amount of data processed this provided a 90% confidence interval of 0.86 dB.

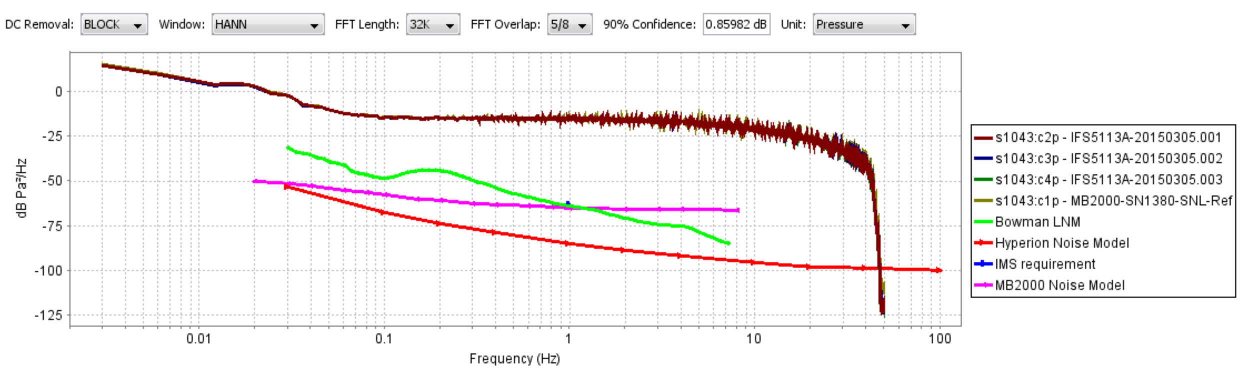

Figure 9 Piston-phone White Noise Power Spectra

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/A sensors under evaluation are plotted below.

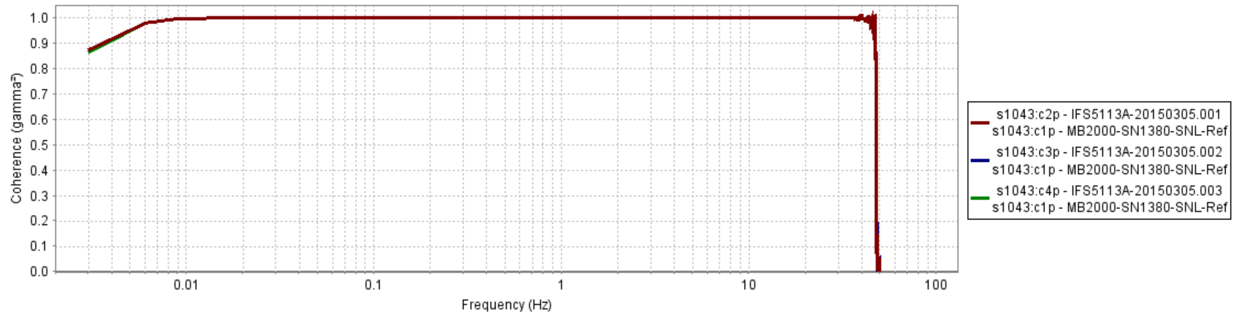

Figure 10 Piston-phone White Noise Coherence

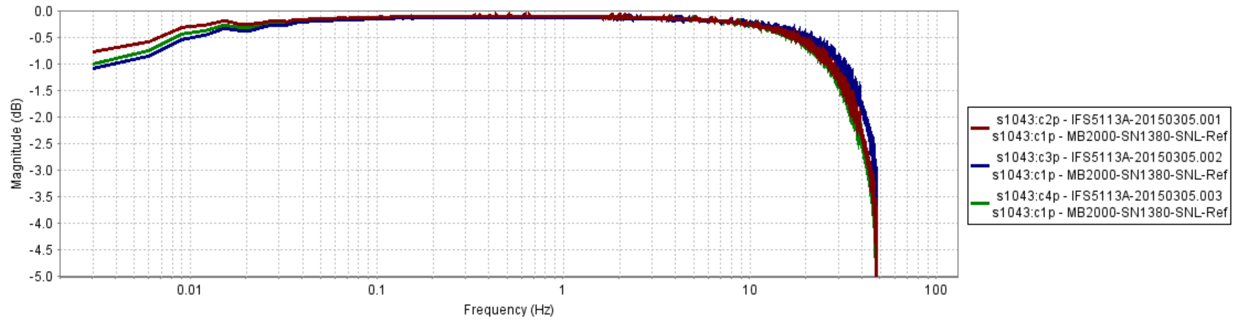

Figure 11 Piston-phone White Noise Relative Magnitude

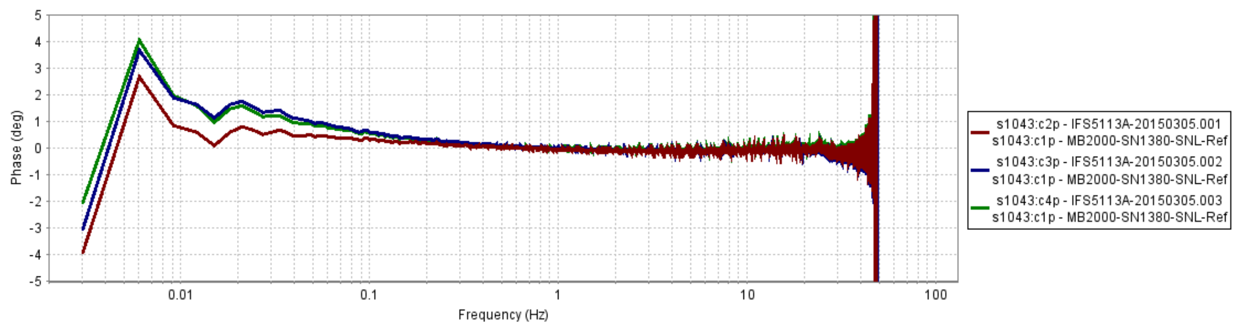

Figure 12 Piston-phone White Noise Relative Phase

Here we can see that the variation in magnitude and phase between the outputs of the MB2000 reference and each of the Hyperion 5113/A sensors are described in the table below. There is sufficient coherence between the Hyperion 5113/A and the MB2000 reference to be able to comment on the relative response over 8.8 mHz to 30 Hz.

Table 13 Piston-phone White Noise Relative Magnitude and Phase, 8.8 mHz – 30 Hz

	Magnitude	**Phase**
5113/A 20150305.001	-0.1 dB / - 1.25 dB	+ 0.83 deg / - 0.22 deg
5113/A 20150305.002	-0.1 dB / -0.98 dB	+ 1.87 deg / - 0.15 deg
5113/A 20150305.003	-0.1 dB / -1.35 dB	+ 1.87 deg / - 0.25 deg

The theoretical response models for both the MB2000 and the Hyperion 5113/A have a 3 dB low frequency corner at 6 mHz and 8.8 mHz, respectively, and then flat beyond that. Given the agreement between the response corrected outputs relative magnitude plots, the evaluated 5113/A sensors are consistent with their theoretical response model in 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 0.86 dB.

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

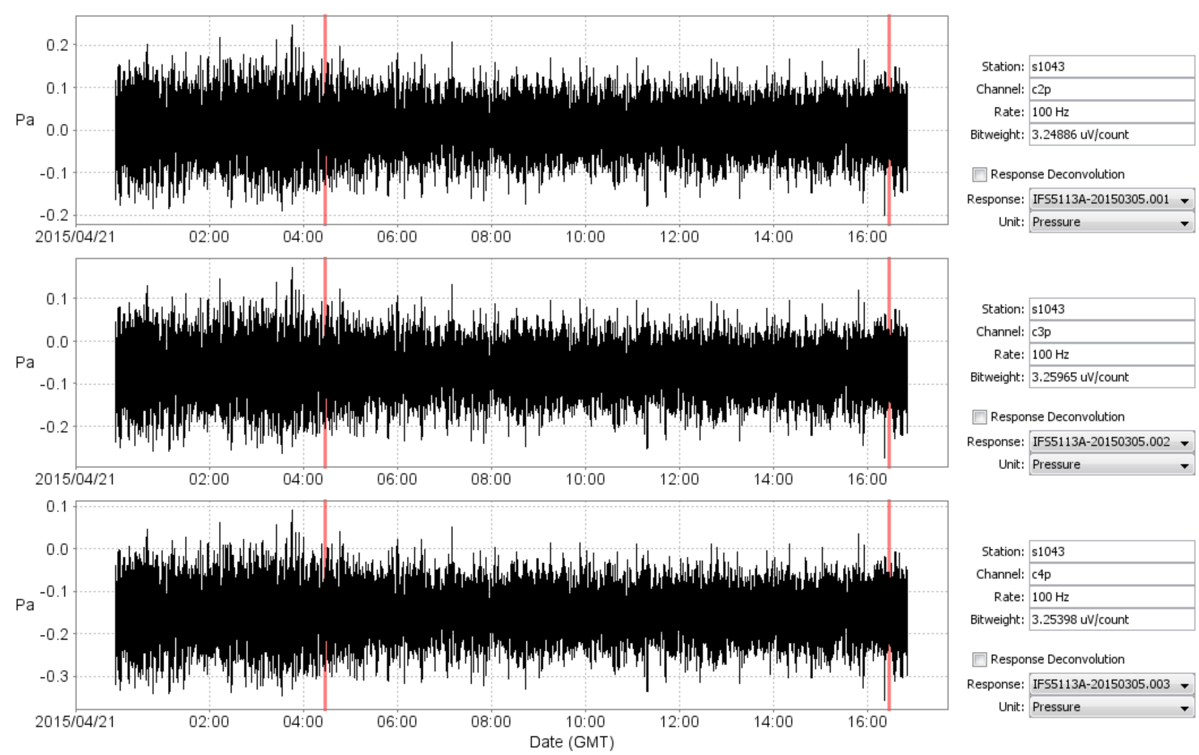

Figure 13 Hyperion 5113/A Dynamic Noise Time Series

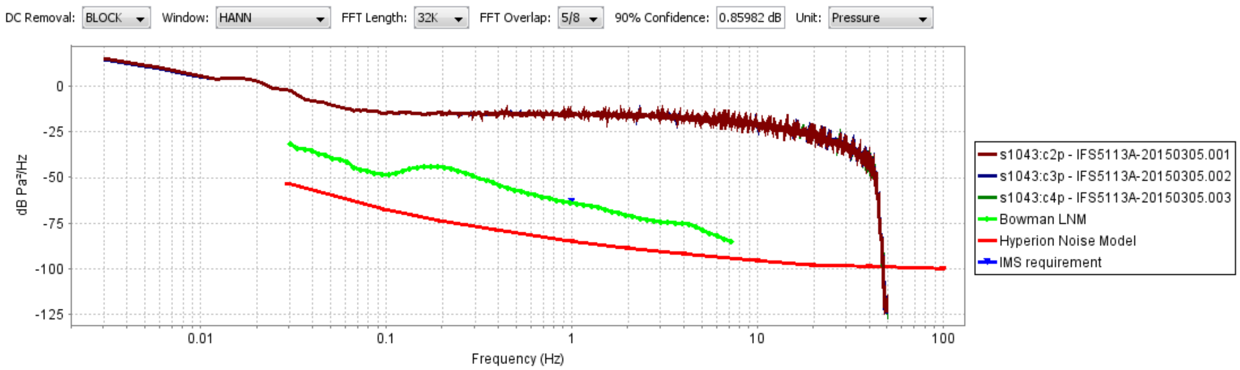

Figure 14 Hyperion 5113/A Dynamic Noise Power Spectra

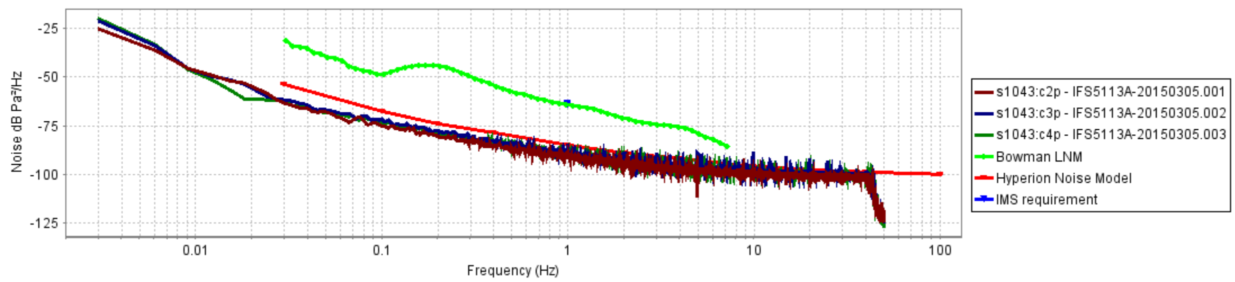

Figure 15 Hyperion 5113/A Dynamic Noise Incoherent Noise

We observe that the 5113/A self-noise, represented by the incoherent noise, is consistent with the 5113/A 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 75 dB above the self-noise at frequencies above 1 Hz.

Even under dynamic conditions, the 5113/A self-noise remains more than 26 dB below the IMS requirement and entirely below the Bowman LNM.

4 EVALUATION SUMMARY

Power:
The observed power consumption of the Hyperion 5113/A was between approximately 1.407 and 1.602 W at 13.24V. The stated power consumption from the sensor specifications was 1.5 W.

Isolation Noise:
The observed self-noise of the 5133/A sensors were entirely below the Bowman LNM across its 0.03 to 7 Hz passband. The sensor self-noise was 26 dB below the IMS requirement, corresponding to being 44 dB below 5 mPa at 1 Hz. The sensor self-noise was consistent with the noise model provided by Hyperion.

Dynamic Range:
The observed dynamic range of the 5133/A sensors was more than 111 dB over 0.0088 – 40 Hz and over 115 dB over 0.02 – 4 Hz, which exceeds the IMS requirement of 108 dB.

Frequency Amplitude Response Verification:
The observed sensitivity at 1 Hz of the Hyperion 5113/A sensors were all between 1.3% 0.056 dB) and 1.59% (0.069 dB) of their provided datasheet sensitivities of approximately 140 mV/Pa The sensitivities were consistent across a range of amplitudes, from approximately 0.013 Pa to 4.7 Pa, differing by less than 0.29 % (0.013 dB) across amplitude. All observed variations in sensitivity across a frequency range of 0.02 to 10 Hz were consistent with the 5113/A response model provided by Hyperion.

Frequency Amplitude Phase Verification:
Broadband measurements of a white noise source indicate that both the Hyperion 5113/A sensors have a response that is flat across 0.0088 to 30 Hz to within 1.35 dB in magnitude and 1.87 degrees in phase. All of the Hyperion 5113/A sensors were consistent in their magnitude and phase response.

Dynamic Noise:
The observed self-noises of the 5113/A sensors, while measuring amplitudes as much as 75 dB above its noise model, were consistent with its noise model.

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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 MB2000 SN 7009.

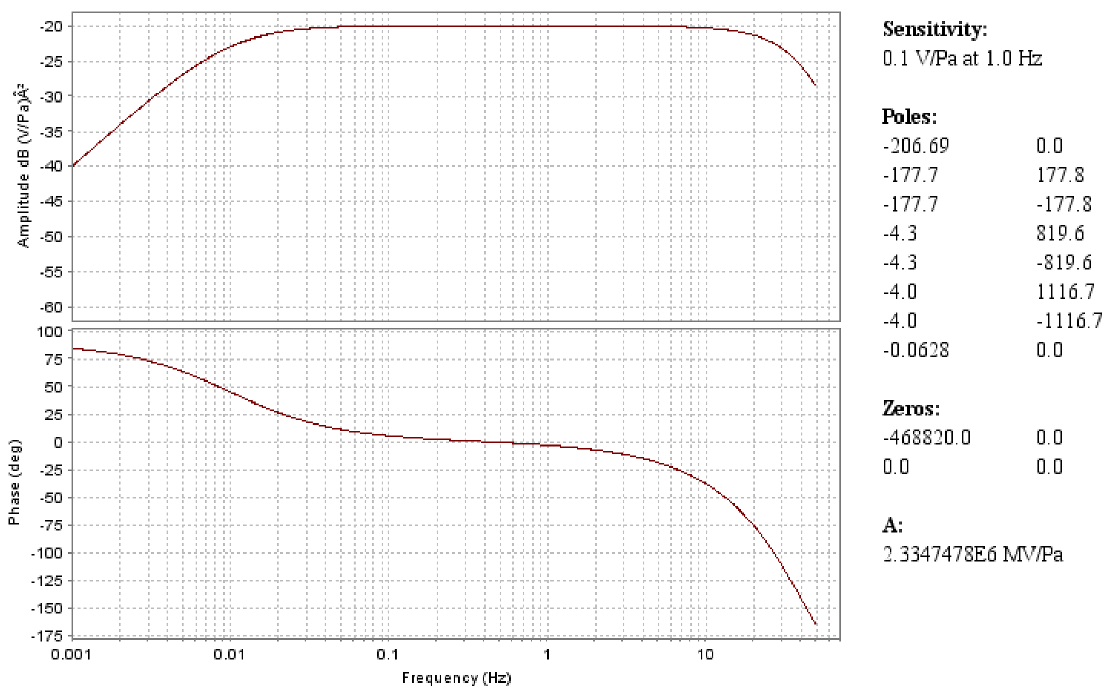
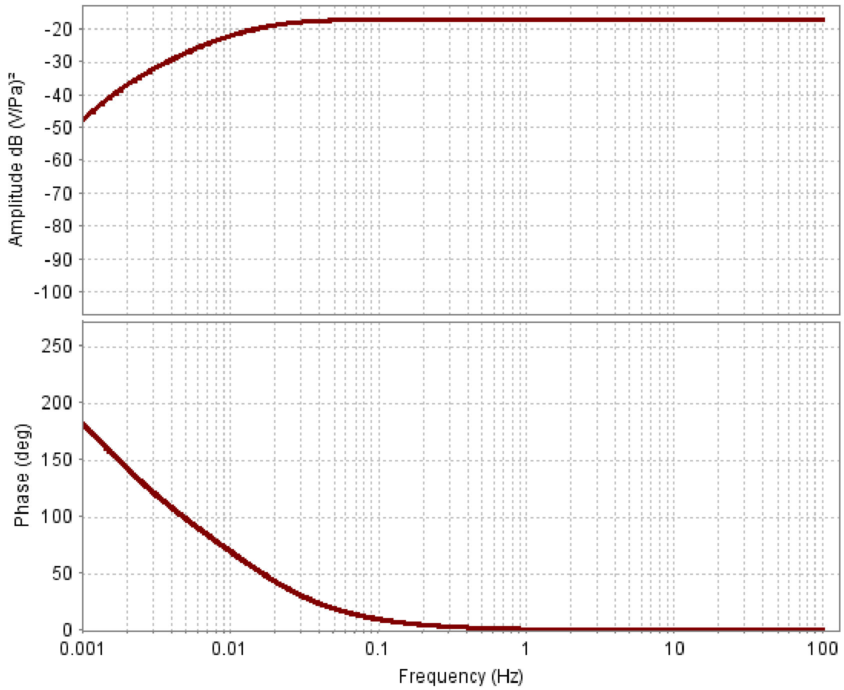


Figure 16 MB2000 Response

Hyperion 5113/A Response

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



Sensitivity:
0.14042 V/Pa at 0.5 Hz

Poles:

-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
0.14048 V/Pa

Figure 17 Hyperion 5113/A #20150305.001 Response

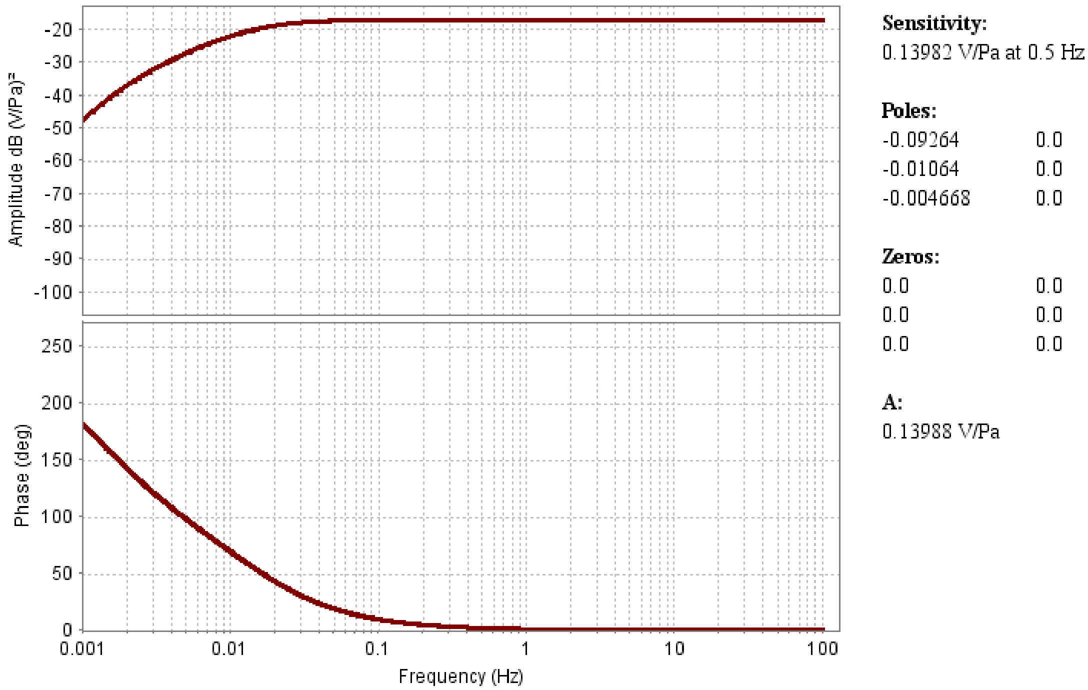


Figure 18 Hyperion 5113/A #20150503.002 Response

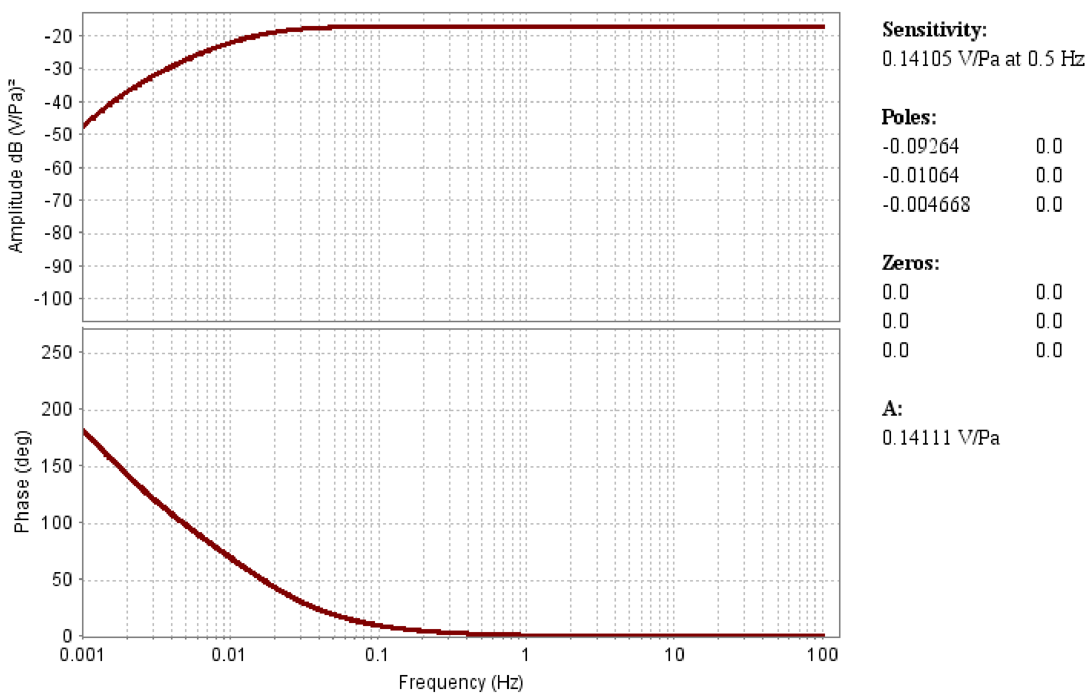


Figure 19 Hyperion 5113/A #20150503.003 Response

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