SAND2022-12287C

Measurement of Infrasound Sensor Self-Noise

Acoustical Society of America
05 December 2022

Nashville, Tennessee

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PSU and SNL were supported by the Nuclear Arms Control Technology (NACT) Program at the Defense Threat Reduction Agency (DTRA). LNE received support from the Provisional Technical Secretariat (PTS) of the Comprehensive Nuclear Test-Ban Treaty Organization.

Cleared for release

Infrasound-Sensor Intercomparison Exercise

Goal: Assess laboratory capabilities and equivalence for,

(1) sensitivity and frequency-response measurement using primary or secondary means and
(2) **self-noise measurement**

Frequency range: 0.01 to 10 Hz

Sensor self-noise: The sensor output with input excitation reduced as low as possible; the noise power added to a measurement by the sensor.

Methods for self-noise measurement:

(1) Isolate from external excitation
(2) Coherent-signal subtraction
~~(3) Deactivate sense element~~

Importance: Is the noise-floor sufficiently low that the sensor can resolve acoustic events near the low-noise ambient background?

The Exercise: PTSAVH.A-C1

PTSAVH.A-C1 was coordinated by the Provisional Technical Secretariat of the Comprehensive Nuclear Test-Ban Treaty Organization with LNE as the Pilot Lab, and it included the Participants listed below.

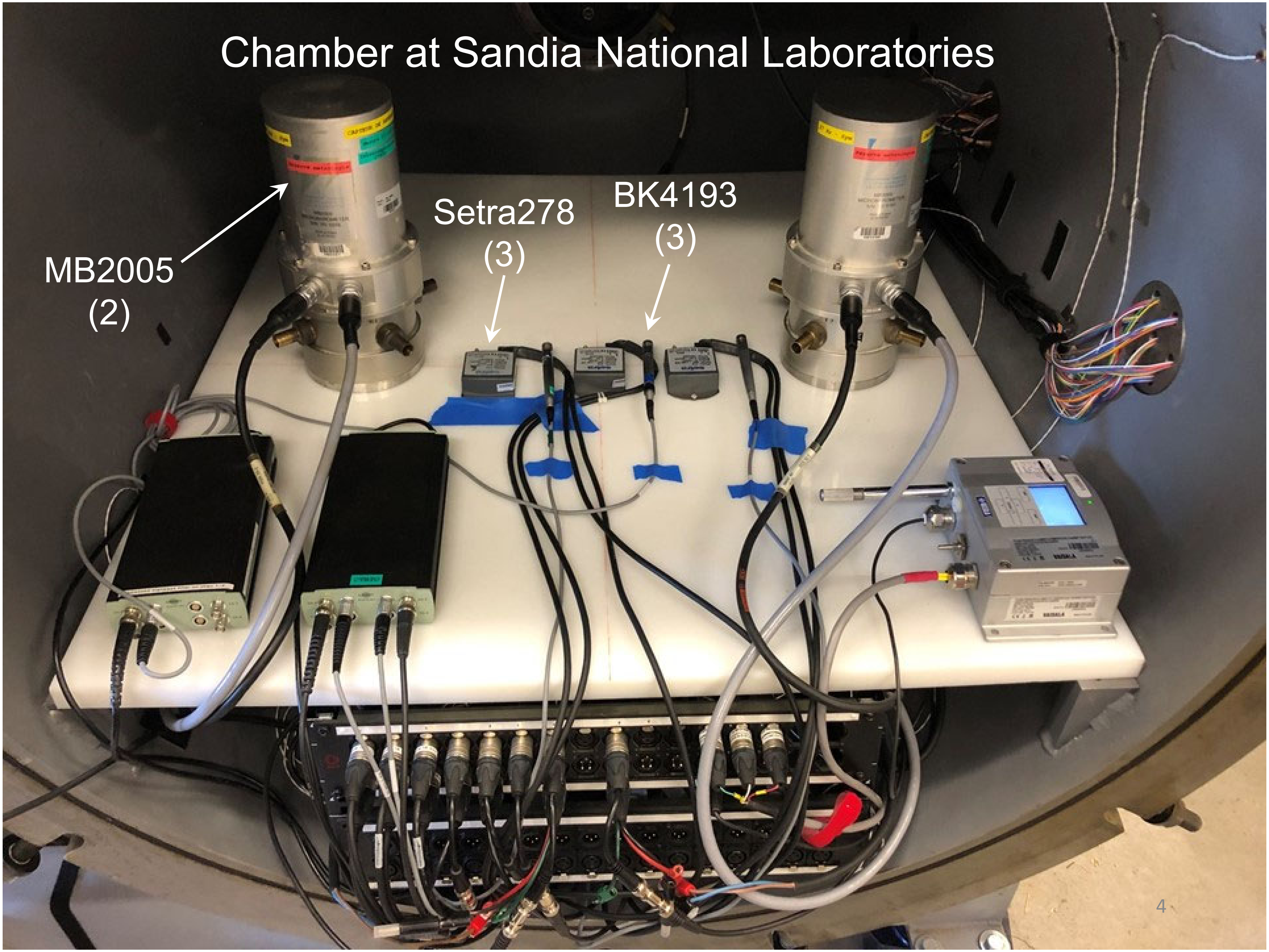
Sensors:

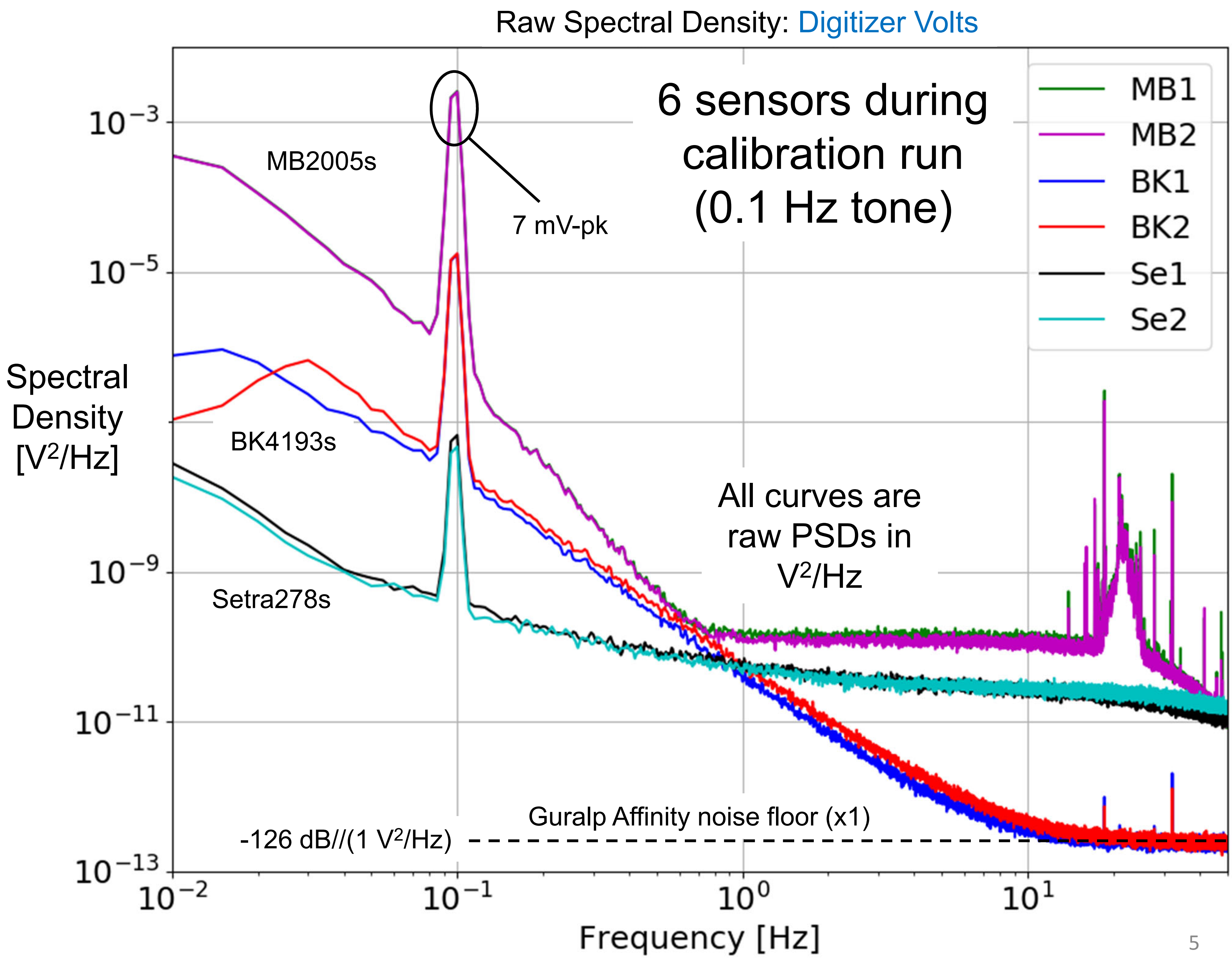
- Two Martec MB2005 microbarometers (MB)
- Two Brüel and Kjær 4193 infrasound microphones (BK)
- Two Setra 278 absolute pressure sensors (Se)

Participants:

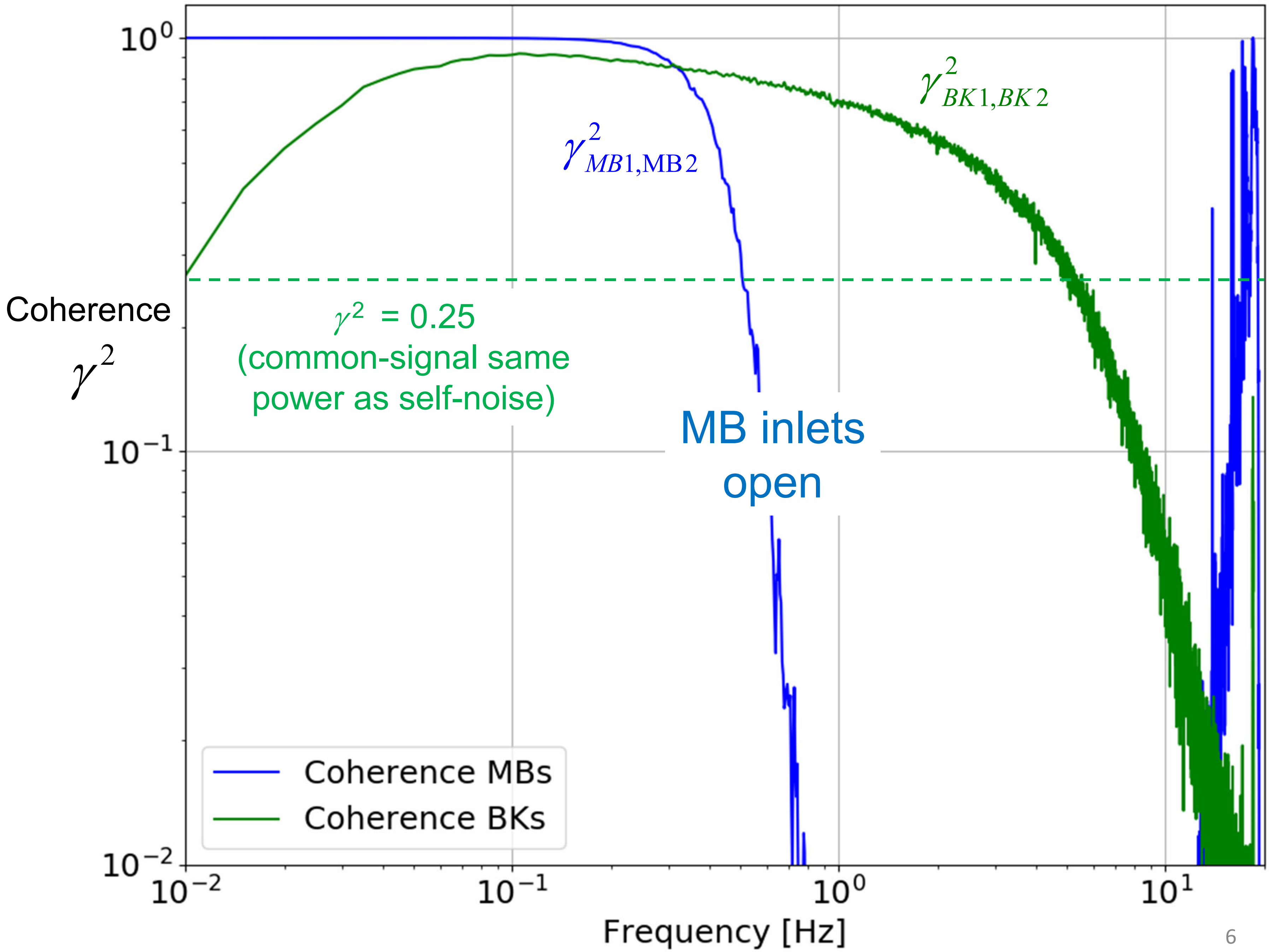
- LNE: Laboratoire National de métrologie et d’Essais
- CEA: Commissariat à l'énergie atomique et aux énergies alternatives
- PTS: Provisional Technical Secretariat
- SNL: Sandia National Laboratories
- NCPA: National Center for Physical Acoustics
- PSU: Penn State University

The infrasound sensors circulated from January 2020 to February 2021 in the following sequence: LNE, NCPA, PSU, SNL, CEA, PTS, LNE.

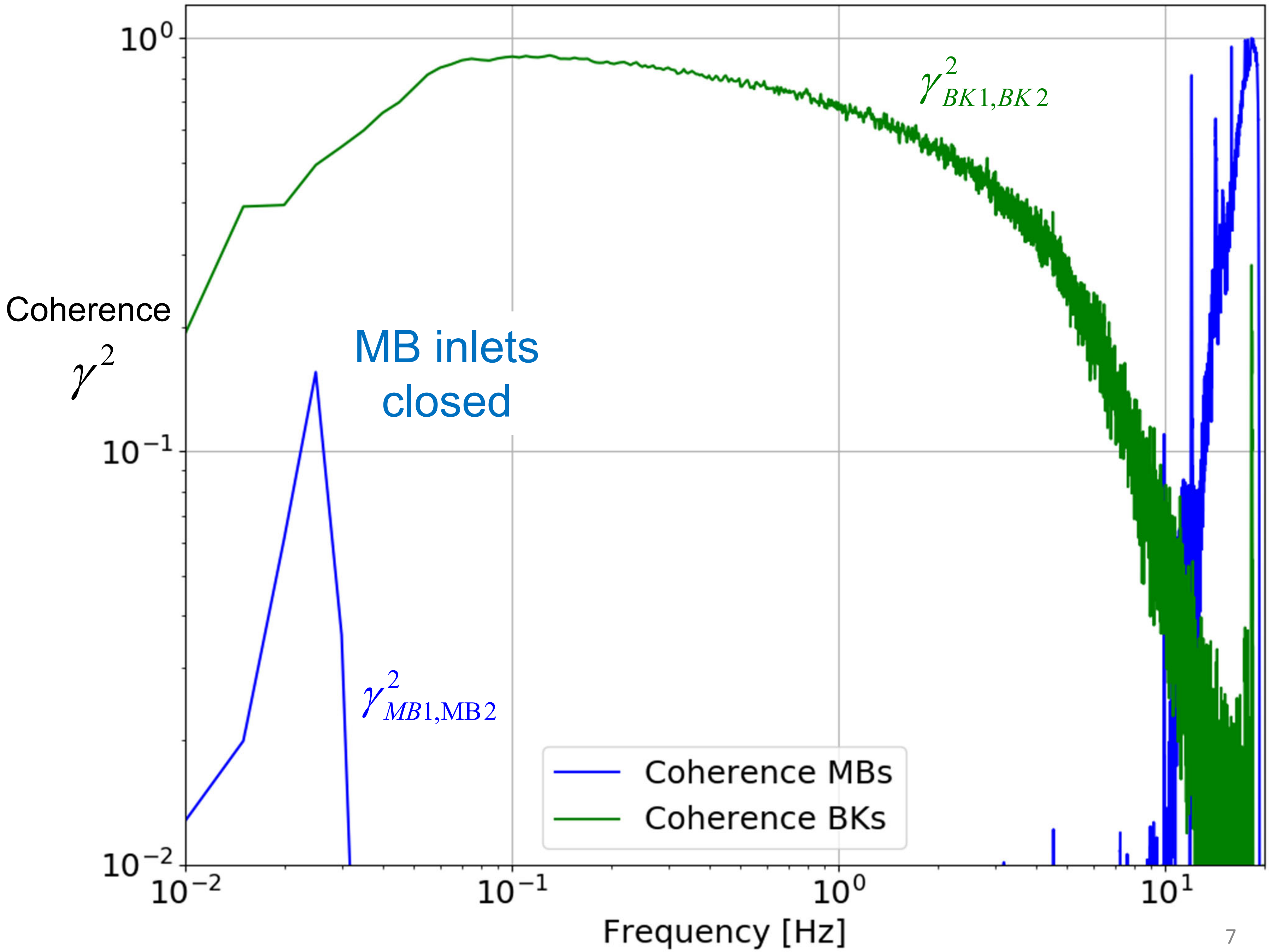

Chamber at Sandia National Laboratories
MB2005
(2)
Setra278
(3)
BK4193
(3)

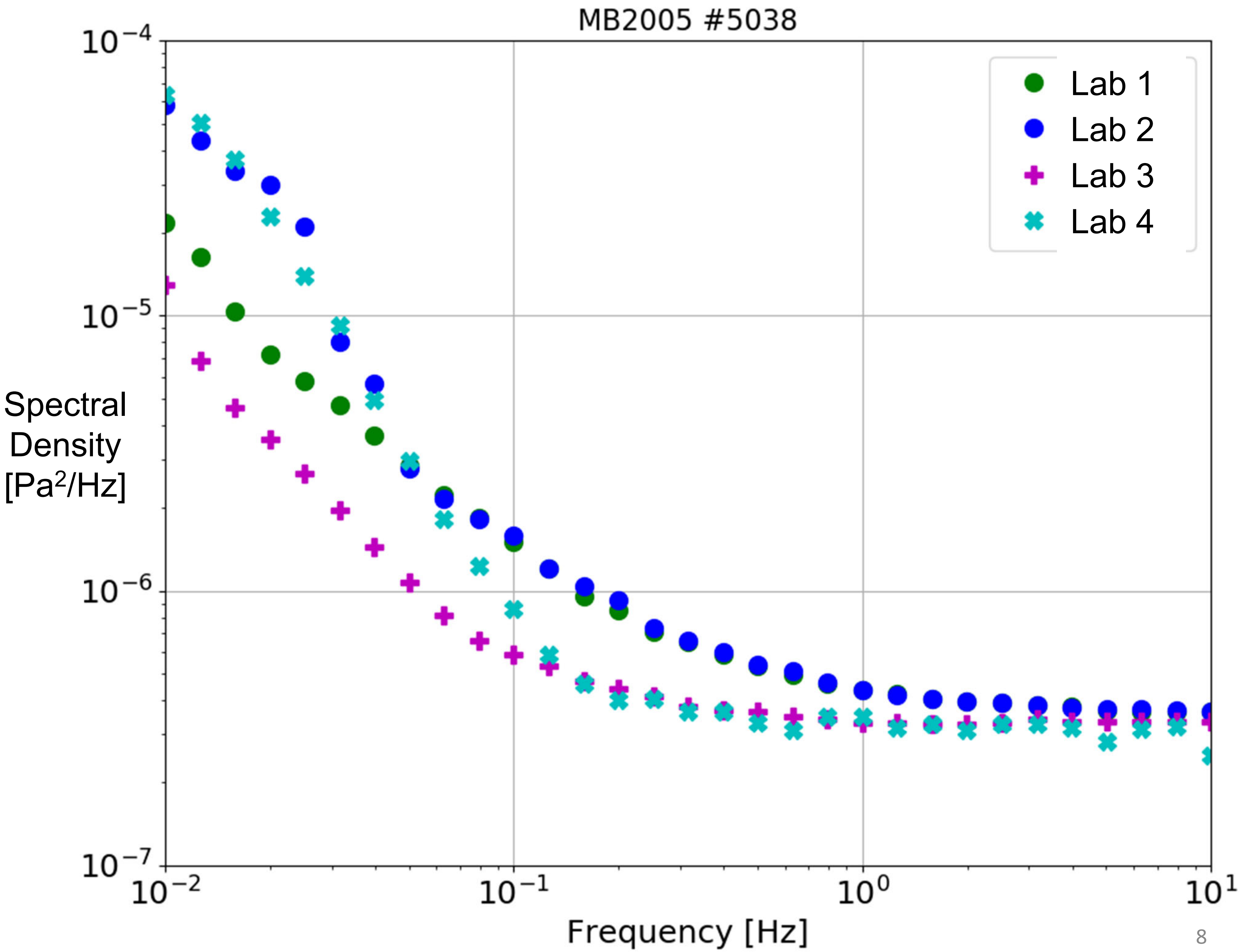


Raw Spectral Density: Digitizer Volts
6 sensors during calibration run (0.1 Hz tone)
MB1
MB2
BK1
BK2
Se1
Se2
MB2005s
7 mV-pk
BK4193s
Setra278s
Spectral Density [V²/Hz]
All curves are raw PSDs in V²/Hz
Guralp Affinity noise floor (x1)
-126 dB//(1 V²/Hz)
10⁻³
10⁻⁵
10⁻⁹
10⁻¹¹
10⁻¹³
10⁻²
10⁻¹
10⁰
10¹
Frequency [Hz]



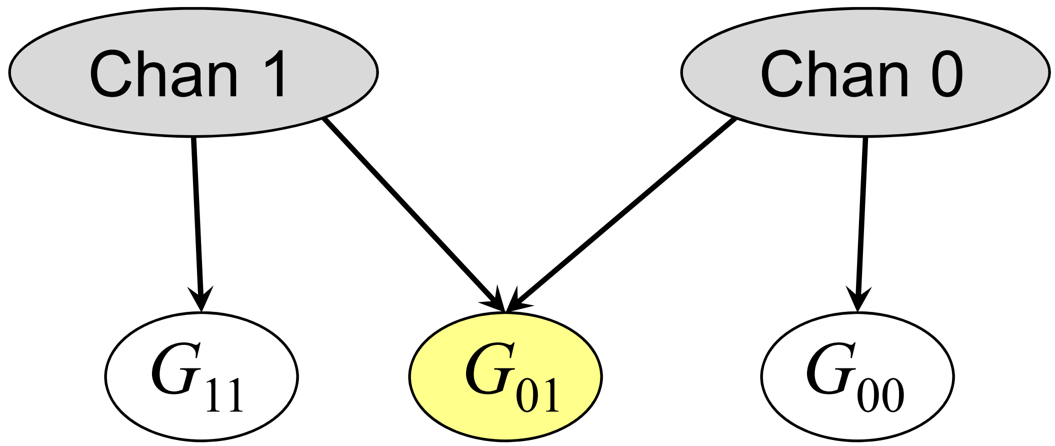
$\gamma^2_{BK1,BK2}$
$\gamma^2_{MB1,MB2}$
Coherence
γ^2
γ^2 = 0.25
(common-signal same
power as self-noise)
MB inlets
open
Coherence MBs
Coherence BKs
10^0
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^0
10^1
Frequency [Hz]


Coherence
γ^2
MB inlets
closed
$\gamma^2_{BK1,BK2}$
$\gamma^2_{MB1,MB2}$
Coherence MBs
Coherence BKs
10^0
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^0
10^1
Frequency [Hz]



MB2005 #5038
Lab 1
Lab 2
Lab 3
Lab 4
Spectral Density [Pa²/Hz]
Frequency [Hz]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}
10^{1}

Coherent-Signal Subtraction: Two-Channels Similar Sensors



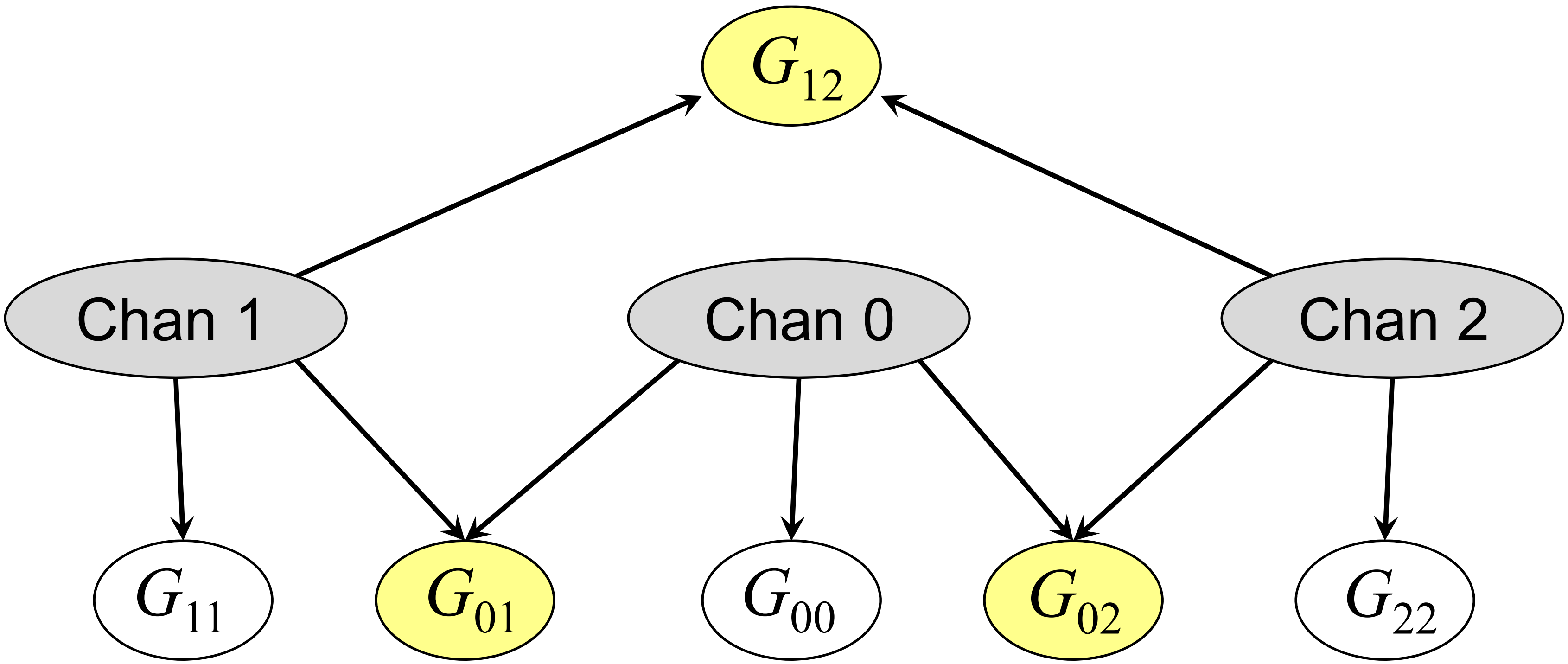
$$\tilde{N}_{00} = G_{00}\left[1 - \sqrt{\gamma_{01}^2}\right]\frac{1}{\left|H_0\right|^2}$$

$$\gamma_{01}^2 = \frac{G_{01}^* G_{01}}{G_{00} G_{11}}$$

$$\tilde{N}_{00} \text{ in } \frac{Pa^2}{Hz}; \quad G_{mn} \text{ in } \frac{V^2}{Hz}; \quad H_0 \text{ in } \frac{V}{Pa}$$

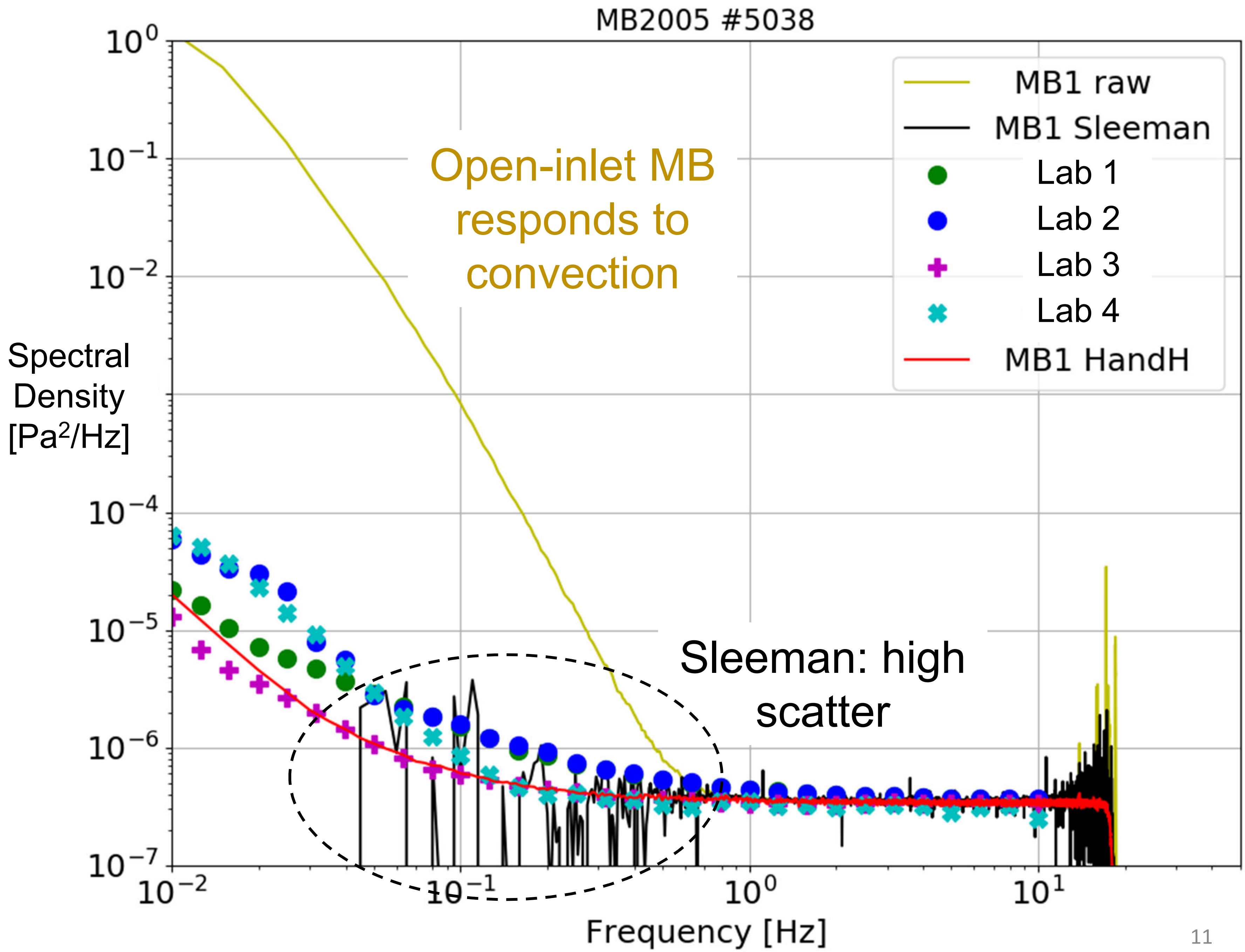
M. P. Horne and R. A. Handler, "Note on the cancellation of contaminating noise in the measurement of turbulent wall pressure fluctuations," Experiments in Fluids 12, pp. 136–139, 1991.

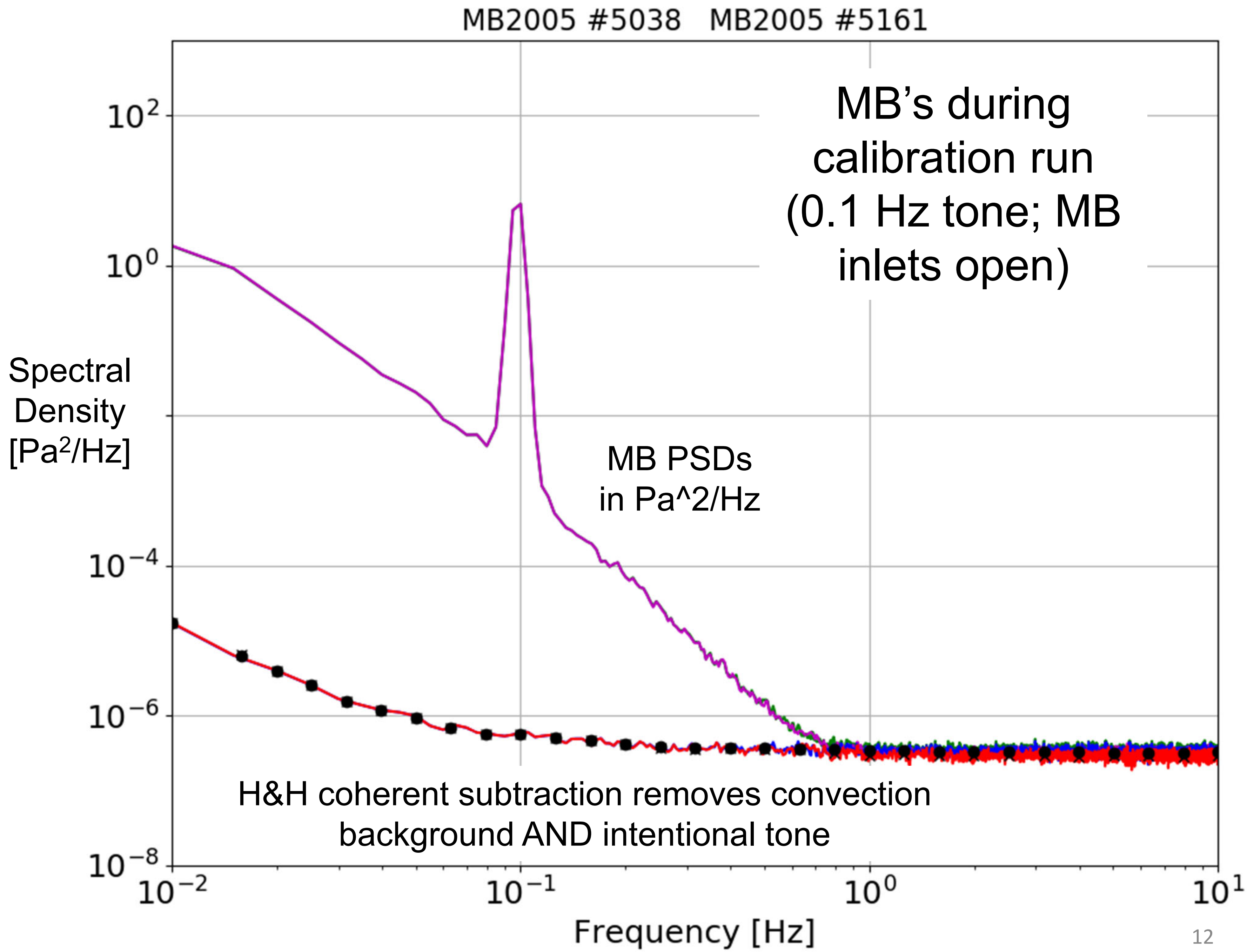
Coherent-Signal Subtraction: Three-Channels



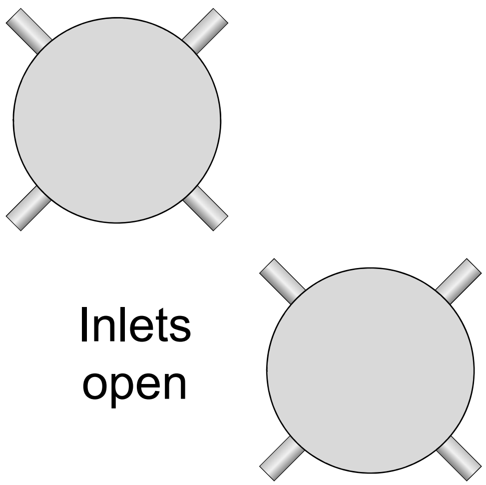
$$\tilde{N}_{00} = G_{00}\left[1 - \frac{G_{01}\,G_{20}}{G_{12}^{*}\,G_{00}}\right]\frac{1}{\left|H_0\right|^2}$$

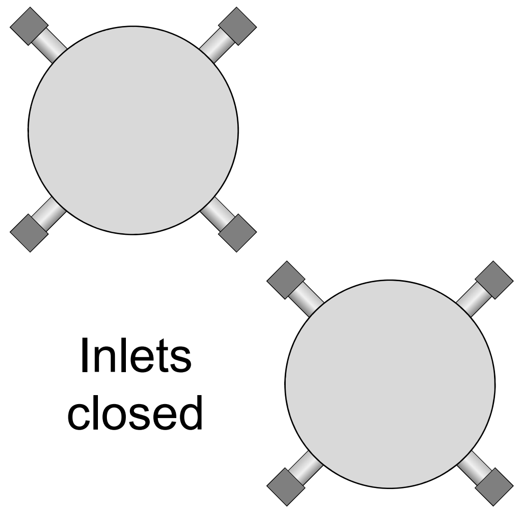
R. Sleeman, A. van Wettum, and J. Trampert, "Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors," Bulletin of the Seismological Society of America, Vol. 96, No. 1, pp. 258–271, February 2006.

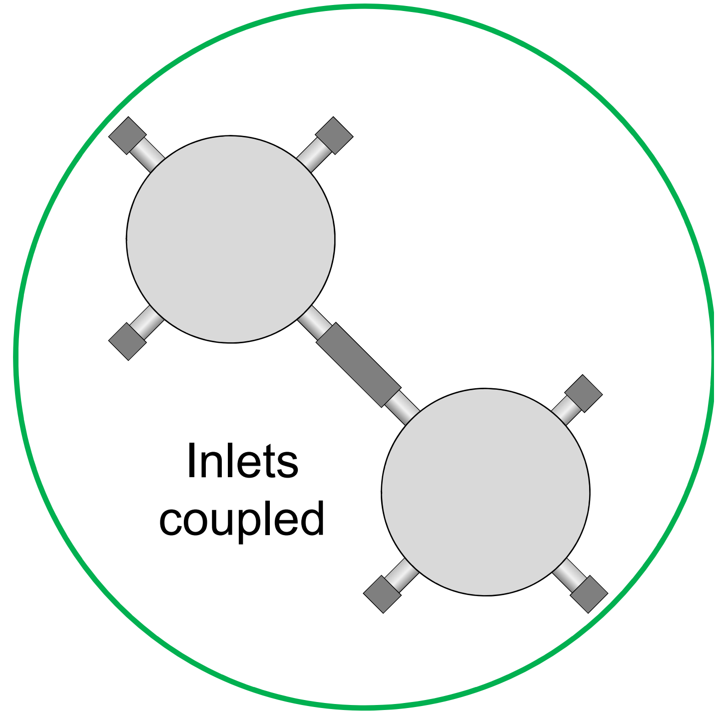

MB2005 #5038
Spectral Density [Pa²/Hz]
Frequency [Hz]
MB1 raw
MB1 Sleeman
Lab 1
Lab 2
Lab 3
Lab 4
MB1 HandH
Open-inlet MB responds to convection
Sleeman: high scatter


MB2005 #5038 MB2005 #5161
MB's during calibration run (0.1 Hz tone; MB inlets open)
Spectral Density [Pa²/Hz]
MB PSDs in Pa^2/Hz
H&H coherent subtraction removes convection background AND intentional tone
Frequency [Hz]

Sensors with Inlet Ports (MB2005)



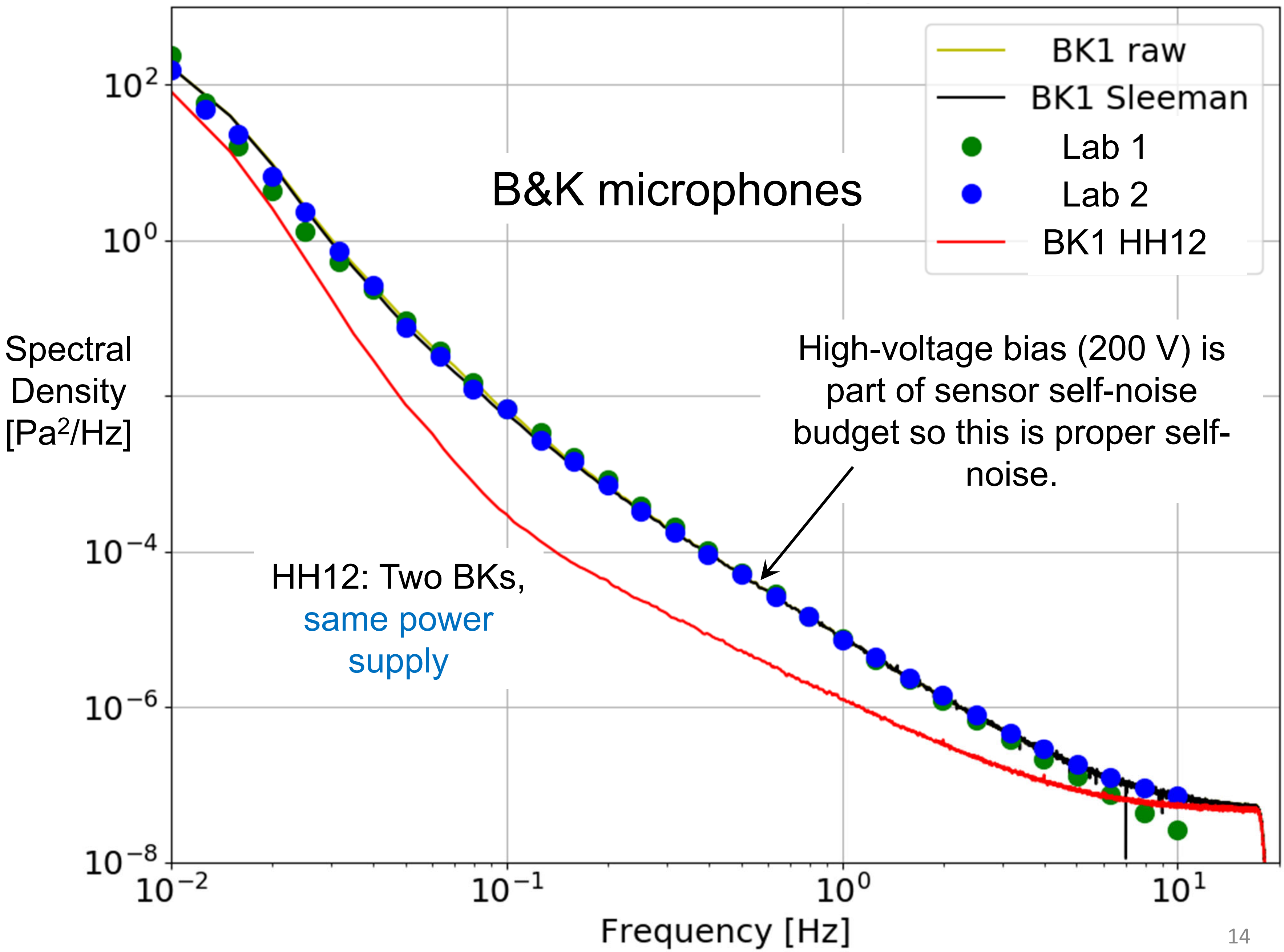




- Potentially large common signal
- Common-signal subtraction OK but prone to differencing error

- Isolation
- Incoherent closed-volume components
- Common-signal subtraction ineffective

- Isolation
- Coherent closed-volume components
- Common-signal subtraction OK


B&K microphones
BK1 raw
BK1 Sleeman
Lab 1
Lab 2
BK1 HH12
Spectral Density [Pa²/Hz]
Frequency [Hz]
High-voltage bias (200 V) is part of sensor self-noise budget so this is proper self-noise.
HH12: Two BKs, same power supply

Recommendations

Basic measurements

- Use at least two sensors of each type
- Plot the narrowband voltage spectral density (V^2/Hz)
- List the parameters of process
  - Sample rate, record length, overlap, window used, number of averages
- Plot the coherence
- Assess the noise-floor of the digitizer

Coherent-signal subtraction

- Types
  - Two-sensor (Horne and Handler)
  - Three-sensor (Sleeman)
- Anticipate errors associated with subtraction of large, nearly equal components
- Check for unintended sensor coupling
  - Electrical cross-talk
  - Shared power

Acknowledgements

Provisional Technical Secretariat
Richard Barham (Acoustic Sensor Networks)
Yacine Sid Ahmed, Benoit Doury, Alfred Kramer (Provisional Technical Secretariat)
F. Larsonnier (Commissariat à l'énergie atomique et aux énergies alternatives)
Carrick Talmadge (National Center for Physical Acoustics)

Back-up Slides

Outline

- Definition of self-noise
- Measurement approaches
  - isolation from ambient
    - in a chamber/box
    - plug inlet
    - find a quiet place
  - subtraction of coherent components
  - de-activation of active element
- Diagnostics
  - Raw voltage spectral density (V^2/Hz)
  - Coherence
  - Noise-floor of DAQ
- Problems
  - isolation
  - coherence
  - spurious response (e.g., temperature fluctuations)
- Coherent-signal subtraction
  - types
  - potential for problems
- Recommendations

Sensor Self-Noise

Definition of Self-noise: the irreducible output of the sensor; the output of the sensor with negligible excitation. Accomplish by isolation and/or coherent-signal subtraction.

Use at least two sensors of the same type.

Use coherence to verify "good" noise-floor measurement.

Report narrowband spectral density, record length, time-domain window, overlap, sample rate, digitizer, digitizer gain.

Minimum (?) for narrowband estimation in 0.01 to 10 Hz range: 200 s records (df = 0.005 Hz, ignore 0*df and 1*df bins); 50% overlap, Hann window; 100 averages (total time = 2.8 hours).

Incomplete isolation from ambient introduces a bias (over-estimate); this error is not a zero-mean random uncertainty.

Measure noise floor of acquisition system to verify that it's sufficiently below sensor noise floor (challenging for B&K microphones); need noise floor of everything after sensor (V^2/Hz useful presentation).

Decibel reference: 1.0 Pa^2/Hz and 10*log10(spectral density).

Sensor Self-Noise: Special Cases

Microbarometers generate heat and, in closed chambers, produce convection, which produces turbulence. Two factors confound coherent-signal subtraction: coherent levels much larger than self-noise levels and potential for turbulence scales to be shorter than distance between inlet ports over some range of frequencies.

Capping microbarometers can isolate from chamber convection; however, capping "adds" another noise source: pressure fluctuations caused by temperature fluctuations in the fore-volume.

Possible method if sensor test must be done inside chamber: port all microbarometers together while capped with respect to interior of chamber. (Some evidence that Horne and Handler coherent subtraction may work with inlets open.)

Possible method if measurement can be done at local ambient pressure: Cluster three or more sensors indoors/outdoors (but not inside a chamber) and use Sleeman for quiet overnight period.

B&K power-supply noise common to all connected microphones; use separate power supply for each microphone, if possible.

Injection of signal: don't do it unless trying to characterize nonlinearity and spurious lines; then use high-purity (?) sine wave, not broadband

Basic Parameters for Self-Noise Measurement (examples)

Case 1

Sample frequency, fs = 200 S/s

usable records, record length = 330, 100 s

File length = 5.7 hours

Window, Overlap: Hann, 50%

Case 2

Sample frequency, fs = 40 S/s

usable records, record length = 700, 200 s

File length = 19.4 hours

Window, Overlap: Hann, 50%

Digitizer [Example: Guralp Affinity]

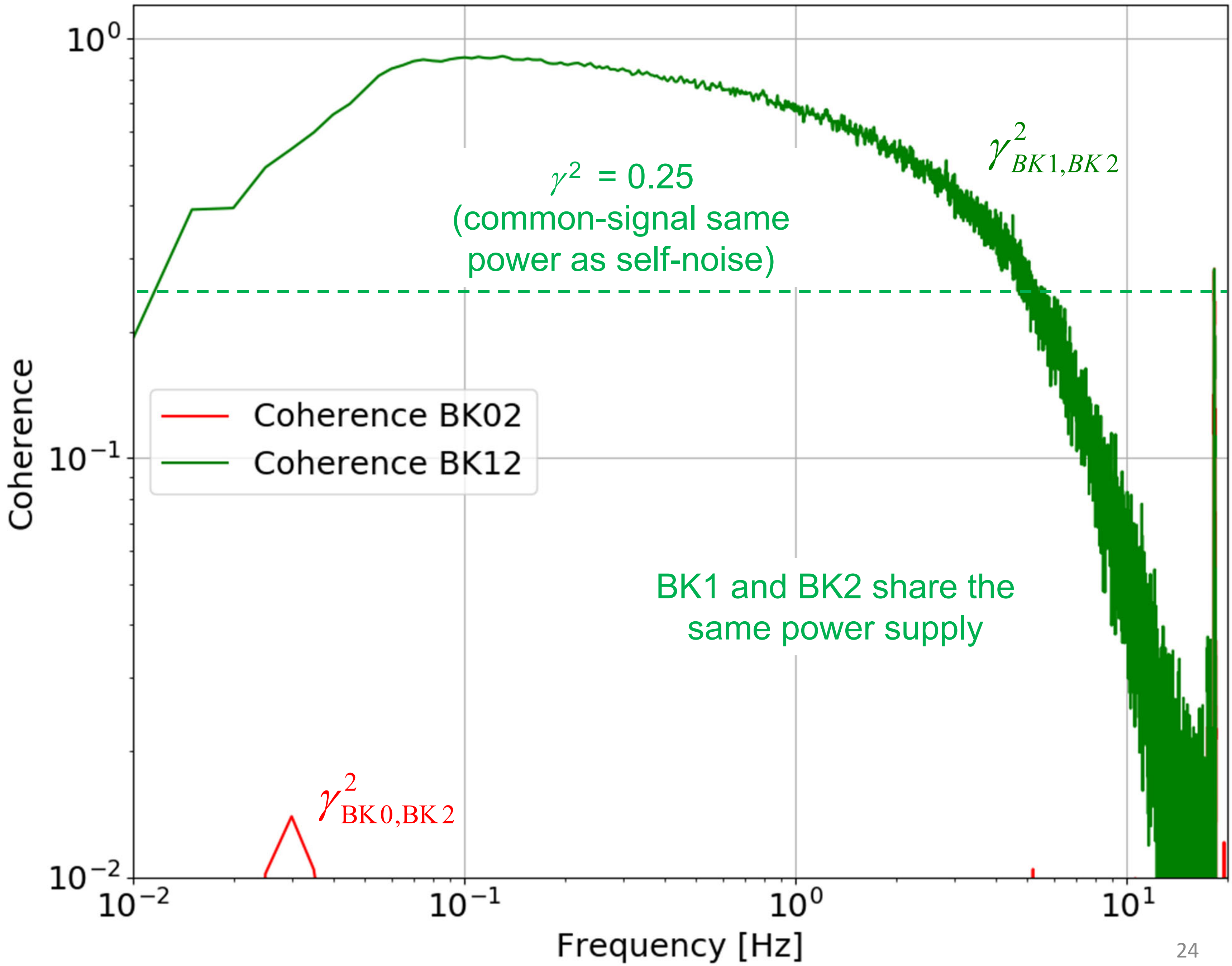
https://www.osti.gov/servlets/purl/1564039
G.W. Slad, Guralp Affinity Evaluation for SNL Infrasound Testbed, Sandia National Laboratories Report SAND2019-10947, Sept 2019.
https://doi.org/10.2172/1564039

Standard set up
- Gain = x1
- Full scale = +/-20 V (40 V range)

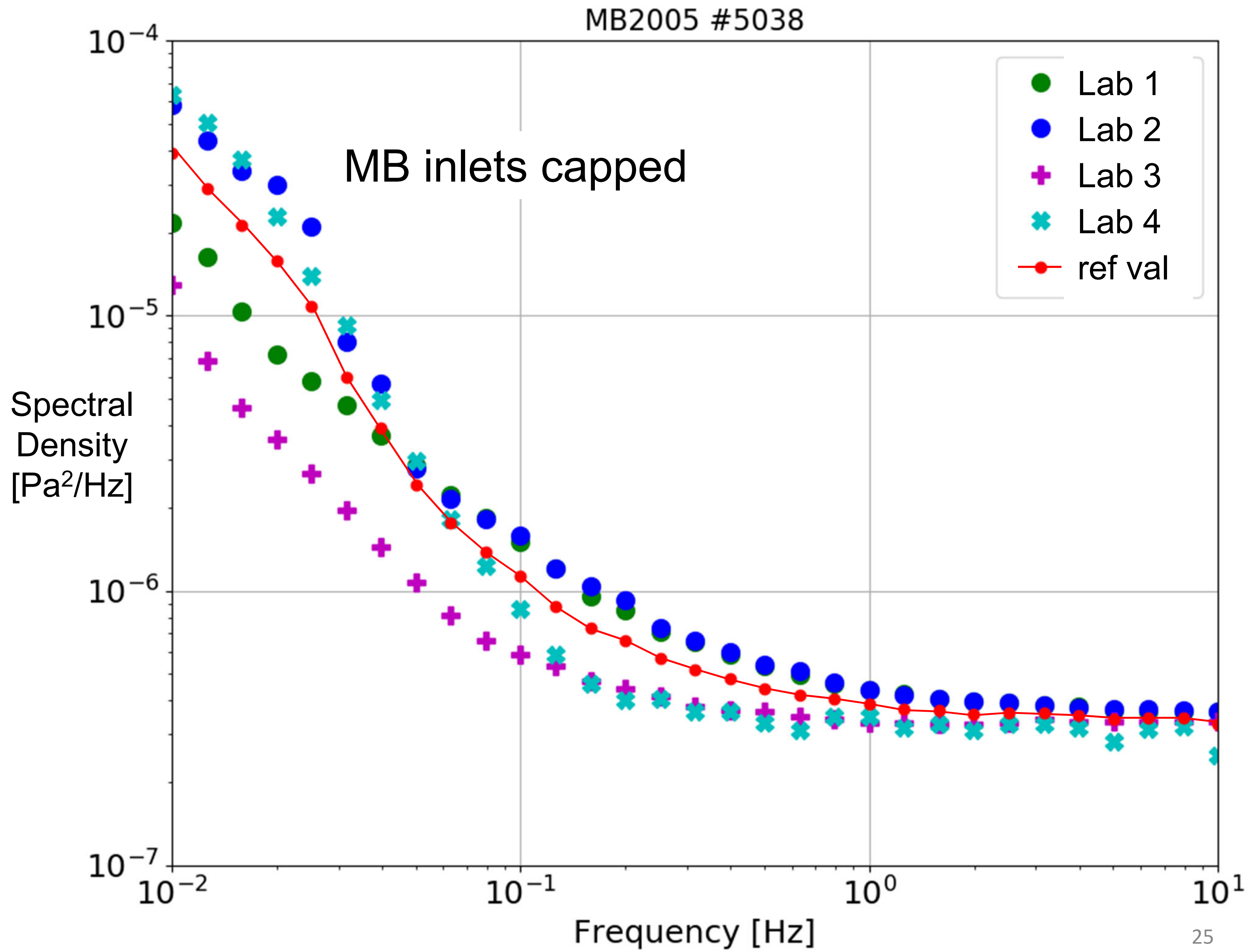
Noise floor (for fs = 200 S/s and x1 gain)
- -126 dB//V^2/Hz; 2.5e-13 V^2/Hz; 500 nV/$\sqrt{Hz}$; 21 bits effective

[100-ohm resistor termination for noise-floor measurement:
- Resistor noise = 1.6e-18 V^2/Hz; 1.3 nV/$\sqrt{Hz}$]

Nominal bit weight = 1.000 uV/count



10^0
10^{-1}
10^{-2}
Coherence
γ^2 = 0.25
(common-signal same
power as self-noise)
$\gamma^2_{BK1,BK2}$
Coherence BK02
Coherence BK12
BK1 and BK2 share the
same power supply
$\gamma^2_{BK0,BK2}$
10^{-2}
10^{-1}
10^0
10^1
Frequency [Hz]


MB2005 #5038
MB inlets capped
Lab 1
Lab 2
Lab 3
Lab 4
ref val
Spectral Density [Pa²/Hz]
Frequency [Hz]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻²
10⁻¹
10⁰
10¹

Outdoor Self-Noise Measurement