Measurement with verification of stationary signals and noise in extremely quiet environments: Measuring below the noise floor

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It can be problematic to measure stationary acoustic sound pressure level in any environment when the target level approaches or lies below the minimum measureable sound pressure level of the measurement system itself. This minimum measureable level, referred to as the inherent measurement system noise floor, is generally established by noise emission characteristics of measurement system components such as microphones, preamplifiers, and other system circuitry. In this paper, methods are presented and shown accurate measuring stationary levels within 20 dB above and below this system noise floor. Methodology includes (1) measuring inherent measurement system noise, (2) subtractive energy based, inherent noise adjustment of levels affected by system noise floor, and (3) verifying accuracy of inherent noise adjustment technique. While generalizable to other purposes, the techniques presented here were specifically developed to quantify ambient noise levels in very quiet rooms used to evaluate free-field human hearing thresholds. Results obtained applying the methods to objectively measure and verify the ambient noise level in an extremely quiet room, using various measurement system noise floors and analysis bandwidths, are presented and discussed. The verified results demonstrate the adjustment method can accurately extend measurement range to 20 dB below the measurement system noise floor, and how measurement system frequency bandwidth can affect accuracy of reported noise levels. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1121/1.4908566>]

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I. INTRODUCTION

In the field of acoustics, there is frequent need to precisely measure audible amplitude sound pressure levels for many purposes including calibration, characterization, documentation, environmental and product safety. When evaluating human hearing performance measurements below the hearing threshold (e.g., -10 dB SPL¹ levels in the 1 kHz $\frac{1}{3}$ octave band) may be required in very quiet, controlled environments. Maximum permissible ambient noise levels have been specified to ensure negligible masking of audiometric test signals (American National Standard Institute, 1999). In this case, these may call for a background noise level 10 dB below the test signal level, or less than -20 dB SPL. Unfortunately, often the measurement system noise floor, the minimum measurement level capability of the system, exceeds such very low acoustic levels. This paper presents a method to accurately measure very low-level stationary test signals, or ambient noise levels in environments designed to have as little ambient noise as possible, e.g., those suitable for testing human hearing thresholds from 20 Hz to 20 kHz. However, the methodologies could be applied to other acoustical measurement conditions when the target signal level is approaching, or lies below the measurement system noise floor.

The International Organization for Standardization (ISO) (2003) criteria for anechoic rooms (typically very quiet) specifies background noise limitations and correction methods for background sound levels near and below the test signal sound pressure level. But to accurately measure and correct very low amplitude test signals, it is still necessary to establish the level of the even lower amplitude interfering noise sources. Unfortunately, acoustic measurement systems have inherent self-noise that limits their usage in very quiet environments (Frederiksen, 1984; Whittle and Evans, 1972). The inherent noise of a modern acoustical measurement system is dominated by the microphone transducer “threshold pressure,” and represents the lowest level of signal which can be usefully converted by the transducer to an electrical output. Below this threshold pressure, output levels are typically masked by the electrical and thermal noise of the microphone (Beranek, 1988). A high quality microphone system might have an A-weighted inherent noise floor of 15 to 25 dBA while some low noise microphone systems might have inherent noise levels as low as 6 dBA. It can be problematic and confusing to attempt to measure acoustic noise or signal sound pressure level in very quiet environments when the target noise or signal level is near or below these levels, referred to here as “inherent measurement system noise floor levels.”

Two general approaches on the measurement of extremely low sound levels are found in the literature: The subtractive energy method (Whittle and Evans, 1972;

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Horonjeff and Ross, 2002), and the dual microphone cross-correlation method (Møller, 1982; Vér *et al.*, 1975; Bjor, 1999). The dual microphone, cross-correlation technique is based upon the premise that signals of interest will be highly correlated between the two microphones, while noise components will be independent and uncorrelated. Instrumentation correlation techniques can be used to separate the desired signal from noise components (Vér *et al.*, 1975; Bjor, 1999; Møller, 1982). The technique is also applicable for extracting speech signals in noisy environments (Yousefian *et al.*, 2010). The correlation methods can be sensitive to microphone size, placement, phase and frequency response characteristics, as well as sound field characteristics. Few measurement results are provided that would encourage implementing a correlation based method. In fact, according to Whittle and Evans (1972), the correlation technique might be better suited to recovering aperiodic signals from noise rather than the more stationary, ambient signals in which we are interested. Therefore, the more straightforward, single microphone subtractive energy approach is investigated in this work.

Applying subtractive energy techniques to perform ambient noise measurement in very quiet environments was covered very clearly in the publication by Whittle and Evans (1972), in which the authors report the method can be used to easily and reliably measure signals 10 to 15 dB below the measurement system noise floor. The work described in that paper was done using AC mains-powered, modular electronic components composing the measurement and signal processing chain necessary to cover the speech frequency range of 100 Hz to 10 kHz. To prevent measurement reading variance or drift due to thermal effects on circuitry performance, long instrument warm-up times were necessary, and component accuracy limitations needed to be addressed to demonstrate reliability. Extending the frequency range reliably is left open, with the authors stating that “more care is necessary.”

Measurement instrumentation has greatly improved since 1972. Here we extend the previous work of Whittle and Evans and contribute new methods to verify the accuracy of this extension of their method. Stationary signal measurements of levels above, near, and up to 20 dB below the noise floor of the measurement system are shown to be accurate using these verification methods. The methods are based upon the subtractive energy formula for the addition of uncorrelated sound sources, and signal averaging. Simply put, the first step is to measure the inherent noise of the acoustic measurement system. Thereafter, the energy level of this inherent noise is subtracted from the target measurements, yielding inherent noise adjusted measured values. Finally, this work introduces simple instrumentation and methods to investigate reliability and to establish confidence in the accuracy of these measurements.

Our primary concern is the measurement of signals in continuous, stationary, ambient noise such as background noise due to air handling systems, electrical hum or low-level acoustic noise emissions from idling amplifiers and transducers. Impacts of non-stationary noise sources like car horns, slamming doors, and aircraft flyovers are not appropriately measured using this technique due to the need for

long averaging times, and might be better estimated by attenuation characteristics of the environment, such as the building structure if measurements are made indoors or distance from attenuating barriers if outside a building environment (Møller, 1982).

As an acoustic sound pressure level decreases in amplitude, the measured value is affected by the noise floor of the instrument, since its inherent system noise adds to the target signal. For uncorrelated signals, a signal with a true level of 20 dB measured with a measurement system noise floor of 0 dB SPL will be measured as 20.043 dB and a -20 dB signal level will be measured as 0.043 dB.² Indeed, a true signal level of 0 dB SPL will be measured as 3.01 dB SPL due to the addition of the two equal signals—the signal being measured and the noise of the system. We therefore propose that to measure stationary, incoherent signals within 20 dB of the inherent noise floor with the method described here, it is necessary to reliably detect a signal level change with better than 0.05 dB precision. While reducing measurement variance to <0.05 dB far exceeds the upper values of the ISO (2003) measurement uncertainty ranges of 0.5 to 2.0 dB, this is attainable by modern precision measurement instrumentation. It is necessary to hold factors such as test room conditions and configuration, signal source instrumentation and configuration, test operators and procedures constant. In addition, rapidly applying a series of reasonably long, overlapped, averaging periods at each measurement step minimizes the duration of the entire experiment. Furthermore, to reduce data acquisition time and potential measurement drift or temporal changes of the ambient environment, all data processing is done post acquisition.

Previously, subtractive energy based, inherent noise adjustment methods were used to measure the ambient noise level in an extremely quiet anechoic chamber within 20 dB above and below the measurement system noise (Ellingson and Helt, 2013). Results shown here extend this work with three different measurement systems of varying inherent noise levels, and also demonstrate the effect of measurement system bandwidth on reported room ambient level results.

New to this work are recently devised methods to verify the accuracy of sub noise floor measurement results. This optional step also is useful to document the impact the sensitivity of the measurement equipment has on test room ambient level results.

Finally, it is common for scientific and acoustic research laboratories to publish ambient noise level specifications for their facilities, without specification of measurement conditions and techniques. The combination of the inherent noise adjustment and measurement verification techniques described in this paper could help objectify the specification of ambient noise levels in extremely quiet environments.

The remainder of the paper is organized as two sets of methods and results, followed by generalized concluding discussion. The first set details the development and implementation of the inherent noise adjustment *methodology itself* including verification of result accuracy. The other set describes the *application* of this technique to ambient noise levels in an extremely quiet room, verification of

measurement result accuracy, effects of varying system noise floor, and the impacts of instrument bandwidth on the results.

II. METHODS: INHERENT NOISE ADJUSTMENT TECHNIQUE

The subtractive energy principle is used to measure periodic or stationary random ambient acoustic levels below the measurement system noise floor as follows: (1) establish the acoustic measurement system noise floor, referred to as the measurement system *inherent noise*, (2) measure target ambient noise conditions, and (3) adjust the ambient noise measurement levels using a subtractive energy based, inherent noise adjustment procedure.

A verification technique is built into the measurement protocol to cross check the accuracy of the inherent noise adjustment method. This involves presenting a series of acoustically calibrated stimuli with decreasing amplitude in the test room and recording the sound pressure level in the room at each step. If the inherent noise adjusted measured results align with the calibrated acoustic step intervals, confidence in the adjustment technique is established. The verification steps are presented in a general manner, but the specific parameters and values chosen should depend on measurement confidence, the stability of the room acoustic character, and any other factors that might influence the degree of verification required. To simplify the performance validation of the inherent noise adjustment method itself, our analysis focuses on the 1 kHz $\frac{1}{3}$ octave frequency band of energy. As this is a standard calibration frequency, it is one of the frequencies at which it is the most likely the characteristics of signal generation, loudspeaker, microphone transduction, and analysis system are sensitive, flat, and stable.

A. Subtractive energy and inherent noise adjustment formulae

Fundamental to the ability to measure stationary sounds near or below the measurement system noise floor is the energy addition formula given in Table I [Eq. (1)]. This formula for decibel addition is valid for incoherent sound sources. The ambient room noise is assumed to be uncorrelated with the internal random noise sources within each acoustic measurement system component. Additionally, the components are battery powered to guard against power line related noise.

Applying the energy addition to this measurement situation results in Eq. (2) (see Table I), where the target ambient noise (unknown, U) is sound source L_1 , the system inherent noise (inherent, I) is sound source L_2 , and the actual measured value (M) is the decibel sum of the two sources.

The kernel calculation underlying the inherent noise adjustment technique is illustrated by the pseudo-code given in Eqs. (3)–(7) (see Table I). Constants MaxDiffDB and MinDiffDB are defined in Eq. (3) and Eq. (4). The value MaxDiffDB sets the lower limit of the adjustment range. It is assumed that 20 dB is attainable (granted the additional 0.043 dB measurement error described above). MinDiffDB is set to the decibel sum of $-\text{MaxDiffDB}$ and 0 dB.³ It is assumed that measurements are repeatedly accurate to within MinDiffDB with modern instrumentation. Successful application of the technique requires sufficient signal averaging to establish measurement values stable to within MinDiffDB. Given values for I and M , Eqs. (5)–(7) solve for the unknown source value, the ambient level U . If the measured value is less than the inherent value plus MinDiffDB, it is assumed to be at the limit of stable measurement range and the ambient level is set to the inherent value less MaxDiffDB in Eqs. (5)

TABLE I. Energy calculations.^a

Description	Formula	Equation	Comment
Energy addition formula	$L_{\Sigma} = 10 \log_{10}(10^{L_1/10} + 10^{L_2/10})$	(1)	Holds for non-coherent sound energy sources, L_1, L_2 in dB.
Measured value = Unknown energy + Inherent energy	$M = 10 \log_{10}(10^{U/10} + 10^{I/10})$	(2)	M = Measured value U = Unknown value I = Inherent noise (measured)
Calculation for Unknown, U	MaxDiffDB=20.0dB	(3)	It can be difficult to apply energy subtractive method at levels below 20 dB.
	MinDiffDB=0.043dB	(4)	Set to decibel sum of $-\text{MaxDiffDB}$ and 0 dB.
(U is referred to in paper as the <i>inherent noise adjusted</i> measurement value.)	If $M < (I + \text{MinDiffDB})$ then	(5)	
	$U = I - \text{MaxDiffDB}$	(6)	
	Else $U = 10 \log_{10}(10^{M/10} - 10^{I/10})$	(7)	
	End		

^aGeneral energy addition formula in Eq. (1). When measuring near or below noise floor, measurements contain both measurement system noise, I , and target signal noise, U , as in (2). The derived energy subtraction formula (7) is used to solve for U when M and I are known (measurable values). Measured values of M very near to I are set to a maximum threshold in (5) and (6), otherwise U is determined to be the energy difference between M and I as in (7). The value of U is referred to in the paper as the inherent noise adjusted measurement value.

and (6), otherwise the unknown value is the decibel subtraction of the inherent source value from the measured source value as in Eq. (7).

B. Application model

Figure 1 shows how the inherent noise adjustment method accurately extends the dynamic measurement range of the acoustical measurement system to 20 dB below the system noise floor. This point is demonstrated by the fact that the solid thin dark line, representing the adjusted levels, extends linearly below the measured system noise floor (dashed gray line at 10 dB) until it intersects the inherent noise adjusted measurement system noise floor, which is represented by the solid gray line at -10 dB. The difference between the dashed and solid gray line represents the error in measurement caused by not using a subtractive method to adjust for measurement system noise.

Ideally, acoustic measurement devices directly measure sound pressure accurately at all levels in a linear fashion. But in reality, a microphone based measurement system presents a barrier to direct measurement of low-level acoustic signals. The barrier, called the *inherent measurement system noise floor* is due to internal microphone and electronic noise sources, and essentially introduces a noise generator into the measurement environment. As target signal measurement levels diminish to this noise floor, the energy in the noise floor becomes an increasing factor in the measured value, eventually dominating as the target energy level falls below the floor level. The actual measured values contain the sum of the inherent noise floor energy and the target acoustic signal energy. Subtracting the inherent noise floor energy from the model's actual measured values, inherent noise adjusted measurement values can be calculated. This can extend the system measurement range as much as 20 dB below the noise floor, establishing an inherent noise adjusted noise floor as shown in Fig. 1.

C. Equipment

The test room was the anechoic chamber P5-161 at the National Center for Rehabilitative Auditory Research, located in Portland, OR. Test conditions included 35% relative humidity, 70°F. The room, described by Ellingson and Helt (2013), was ventilated at a constant 325 CFM rate. Primary measurement instrumentation included the following.

1. Microphone

A microphone with the lowest available inherent noise specification was chosen. Ideally, the testing room ambient noise level in the 1 kHz band will be less than 20 dB below the microphone noise floor to fully investigate the inherent noise adjustment model. The microphone selected was a Brüel & Kjær® type 4955 (www.bksv.com) low noise microphone and preamplifier, with an overall noise floor not to exceed 6.5 dBA over a 10 Hz to 20 kHz bandwidth.

2. Signal acquisition, processor, and averaging

Also referred to as the signal analyzer, a Brüel & Kjær PULSE® LAN-XI based analyzer with LabShop® Version 16 software was used to digitize, filter, and average the microphone signal. In order to remove low frequency signal components, a 22.4 Hz high pass filter was applied to microphone input channels. To improve the signal to noise ratio (S/N), all signal measurements were averaged over a period of 180 s. The analyzer “CPB_spectrum_averaging” mode (constant-percentage-bandwidth frequency-spectrum averaging) was used for $\frac{1}{3}$ octave analysis.

A schematic and pictorial view of acoustical signal generation instrumentation is shown in Fig. 2(A). Additional details include the following.

a. Random noise generator. The Pulse LAN-XI LabShop instrumentation also supports signal generation. The signal generator parameters were fixed at 0 dBV (1 VRMS),

FIG. 1. Model illustrating the problems measuring near or below the system noise floor and how measurement range can be extended by applying a subtractive energy type method. For a system with inherent noise level of 10 dB SPL as shown, measurement error begins to accumulate at levels of 30 dB SPL and increases down to the noise floor level. Adjusting measured values for noise floor energy contribution permits measurements to be made up to 20 dB below the noise floor.

FIG. 2. Test signal generation path. (A) The signal generator output is fed to an amplifier (gain = 1 x) and presented as 0 dBV (1 VRMS) at J1. The signal amplitude is reducible by various combinations of unbalanced “T” attenuators, then connected to the loudspeaker. With jumpers as shown at J1, J2, J3, J4, –35 dBV (17.8 mVRMS) will be applied to the loudspeaker. (B) The attenuation circuitry is implemented using precision metal film resistors on a “breadboard” substrate for ease of assembly and reconfiguration. Clip-on type test leads are used to inject signals at left side and pick off attenuated signals on the right side.

pink filtered, 25.6 kHz bandwidth random noise with signal either on or off. A custom built, low noise buffer amplifier based upon an inexpensive MAX4299 stereo driver (www.maxim-ic.com) was connected to the generator output as a loudspeaker driver. This configuration generated approximately 70 dB SPL @ 1 kHz of acoustical room energy at a distance of one meter. Most any modern signal generator and power amplifier meeting or exceeding CD-DA (Compact Disk Digital Audio) specification should suffice. Of importance are high S/N ratio, low harmonic distortion, and low quiescent noise level. The test system used for this study with no applied signal had quiescent noise of 110 μ VRMS over a 22 Hz to 22 kHz bandwidth. Over the same bandwidth, a 1 kHz test signal at 70 dB SPL driving level, had S/N ratio >90 dB, with ratio of the sum of all harmonic frequency and noise components (THD+N) <0.5% and absolute amplitude sum of all such components <4 mV.

b. Attenuators. A custom built set of single-ended, unbalanced, passive attenuators of simple “T” design was created as pictured and described in Fig. 2(B). Various combinations of attenuation are used to reduce the signal amplitude delivered to the loudspeaker from 0 dBV to –65 dBV in 5 dB step sizes. Using amplifier “tail-end” attenuators instead of reducing signal generator volume helps maintain maximum signal to noise ratio at the loudspeaker acoustic output which helps ensure reliable experimental results (Ellingson and Dille, 2010). The actual attenuation accuracy is not highly critical in this application, however metal-film resistor composition can minimize the contributions of attenuation circuitry to the noise levels.

c. Loudspeaker. Realistic® Minimus-0.3 full range loudspeaker. RadioShack® catalog number 40-1250. Specifications: 240 Hz to 20 kHz; 8 ohm, 7 W. Transducer 1 kHz sensitivity is 70 dB SPL @ 1 VRMS. Overall size is approximately 4 in. (10 cm) per side. Selection is not highly critical but the item selected needs to be physically small enough to be freely operate inside the acoustic isolation box described next.

d. Sound isolation box. The acoustic test chamber enclosure from a Frye Fonix® 8000 hearing aid analyzer system was used as an acoustic isolation box as pictured in Fig. 3. The frequency dependent (dB SPL) and overall (dBA) acoustic isolation of the box was measured with results included in Fig. 3. The measurement procedure included simultaneous averaging of two identical model microphone signals, one inside the box and one immediately external to the box in response to a random noise acoustic stimulus, positioned one meter distant. The measured isolation of 44.82 dBA @ 1 kHz closely agreed with product specification of 45 dBA @ 1 kHz.

The purpose of the isolation box is to maintain high S/N ratios while reducing the room-under-test acoustical energy stimulus signal. Depending on room conditions, it might not be necessary to apply test signals in an isolation box. When the room-under-test ambient noise level or the measurement system noise floor level exceeds an applied stimulus test signal level with reasonable S/N ratio (>MaxDiffdB) by an amount greater than MinDiffdB, there is nothing to be gained by isolating test signals since the testing conditions

FIG. 3. (Color online) Sound attenuating enclosure detail and attenuation performance. With the measurement microphones placed inside and the top cover closed, the test enclosure has measured acoustic isolation of approximately 45 dB @ 1 kHz. The transducer used for test signals emissions in the room-under-test is located underneath the microphones in the picture at left. Inherent measurement system noise floors are measured with the box located in a quiet room, microphones inside the box and the cover closed.

are beyond the range of the inherent noise adjustment algorithm parameters.⁴

D. Measurement technique

As previously reported by Ellingson and Helt (2013), the preliminary ambient noise level in the test room was -3.44 dBA recorded in May 2013. This measurement was arrived at using a 0 dBV free field acoustic signal level with a 0 dB to 90 dB attenuation set with 10 dB increments. These test results indicated attenuation levels greater than 70 dB were unreliable either due to loudspeaker drop out at such low levels ($\leq 316 \mu\text{VRMS}$) or the attenuation circuitry noise was dominating measurements. To achieve very high amounts of acoustic attenuation while maintaining adequate S/N ratio, a dual stage attenuation approach was devised. This consisted of operating the loudspeaker inside the isolation box while undertaking two measurements at each 0 dB to 65 dB attenuation step once with the box open, once with it closed. The box closed condition effectively adds about 40 dB of attenuation. This resulted in two, overlapping signal ranges at the 1 kHz frequency range, 0 to -65 dBV with box open and -40 to -105 dBV with box closed.

The measurement technique is as follows:

- (1) Establish inherent measurement system noise floor, i.e., determine inherent system noise: (a) calibrate microphone to known acoustical reference, e.g., 94 dB SPL, (b) inside test room, place microphone inside isolation box and close cover, (c) acquire sufficient averages until measurement is stable, for this study the average period will be 180 s for all measurements, (d) save averaged result as I .
- (2) Make a series of measurements, M : (a) position microphone 1 m away from box, in direct radiation field of loudspeaker located inside of box, (b) make and save an averaged measurement of ambient room level with no signal applied, (c) with box open and signal on, make and save a series of averaged measurements, one at each 5 dB attenuator step from 0 dBV to -65 dBV, and, (d) with box closed and signal on, repeat the previous series of saved, averaged measurements at each attenuation step.
- (3) Using the saved M results set and saved I value, create a corresponding set of inherent noise adjusted results, U , using Table I, Eqs. (5)–(7).

ISO (2003) calls for measurement averaging periods of 30 s when measuring frequencies ≤ 160 Hz and 10 s when measuring ≥ 200 Hz. The measurement averaging period of 180 s used for each measurement in this experiment was empirically determined by observing a real time $\frac{1}{3}$ octave band analyzer display and associated A-weighted-level meter readout. Frequency band level changes and meter readings stabilized at 60 s but for additional insurance an insurance factor of three was applied. More efficient averaging periods could be used, possibly varying depending on the target center frequency and target frequency bandwidth (Møller, 1982).

III. RESULTS: INHERENT NOISE ADJUSTMENT TECHNIQUE

Table II contains a numerical summary of the measurement technique results. Table II(a) displays the various test signal and attenuation configurations used for the measurement results reported in Table II(b). The measured and associated inherent noise adjusted results for the Box Open and Closed conditions are shown in the upper four rows of results in Table II(b). The measurement system inherent noise floor (Inh NF) is -10.59 dB SPL measured in Signal-Off/Mic-in-box/Box-Closed conditions. The measured room ambient noise level is -10.62 dB SPL in Signal-Off/Mic-out-box/Box-Open conditions. The difference of 0.03 dB is less than the MinDiffDB algorithm parameter, which results in an “ideal case” inherent noise adjusted ambient room level of -30.59 dB SPL. The Signal-On/Box-Open measured results begin to increasingly deviate from attenuated loudspeaker signal levels around -40 dBV. The Signal-On/Box-Closed measured results begin deviating from test signal levels at 0 dBV since the box has similarly attenuated the acoustical signal by 40 dB.

The most interesting cells in the table are in the Signal-On/Box-Closed condition, when the measured values fall in the measured inherent noise floor range, and the cell to cell variance in adjusted measured results becomes negligible. If the adjusted measured values have settled higher in amplitude than the adjusted measured ambient room level (Box-Open, Type Adj = -30.59 dB SPL), the settled measurement values indicate the actual ambient room level. If the adjusted measured values are essentially equivalent to the adjusted measured ambient room level, the actual room ambient level is even lower than the adjusted measured ambient room level. In the latter case a reduction in the measurement system inherent noise floor would be required to accurately measure ambient room level. As applied to Table II(b) results, the actual room ambient level is less than -30.59 dB SPL in the 1 kHz $\frac{1}{3}$ octave frequency band. For reference, the threshold of hearing is defined as 0 dB SPL (20 μPa) at 1 kHz. An adjusted measurement value of -30.59 dB SPL is equivalent to 0.591 μPa .

For purposes of attenuation accuracy analysis, the lower half of Table II(b) contains calculated differences between successive test signal presentation levels for both measured and adjusted results in the Box-Open condition, and error information for the Box-Open condition. The effect of inherent noise on measured attenuation is seen as increased error at test signals which approach the measurement system noise floor of -10.62 dB SPL. The attenuation error calculated using adjusted results is generally quite stable and reasonable. The -4.74% error at the -5 dB position could be reduced by more precisely selecting attenuation components.

A graphical view of measured and adjusted results for Box-Open/Box-Closed conditions is shown in Fig. 4. For comparison purposes, the plot is similar to the experimental model shown in Fig. 1. The measured inherent system noise floor is plotted at -10.59 dB SPL. The measured ambient room level is plotted at -10.62 dB SPL, and the noise adjusted result is plotted at -30.59 dB SPL (limited by our adjustment algorithm maximum difference parameter,

TABLE II. Acoustic test signal conditions (a) with measured and calculated inherent noise adjusted results (b) for 1 kHz $\frac{1}{3}$ octave frequency band.^a

(a) Acoustic Test Signal Conditions																
Test Signal At Generator	Signal Off		Signal On, Level of Test Signal Applied to Loudspeaker, dBV													
			0	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50	−55	−60	−65
			mVRMS													
	Inh NF	Amb Lev	1000	562	316	178	100	56.2	31.6	17.8	10.0	5.62	3.16	1.78	1.00	0.56
Pink-Filtered Random Noise 0 dBV (1 VRMS) ~50 dBSPL	Test Signal			5		5		5		5		5		5		5
	Atten Set	Mic inbox			10	10			10		10	10			10	10
		Mic outbox					20	20	20				20	20	20	20
										30	30	30	30	30	30	30
(b) Measured and Inherent Noise Adjusted Results, Attenuation Performance																
Type		Measured (Meas) and Inherent Noise Adjusted (Adj) Results														
Box Open dBSPL	Meas	−10.62	46.51	41.75	36.63	31.71	26.30	21.40	17.21	12.30	7.38	2.60	−2.72	−6.38	−9.10	−10.10
	Adj	−30.59	46.51	41.75	36.63	31.71	26.30	21.40	17.20	12.27	7.31	2.38	−3.50	−8.46	−14.49	−19.87
Box Closed dBSPL	Meas	−10.59	3.70	−0.68	−5.05	−7.94	−9.72	−10.27	−10.53	−10.60	−10.61	−10.65	−10.65	−10.65	−10.66	−10.62
	Adj		3.53	−1.15	−6.47	−11.34	−17.14	−21.78	−27.11	−30.59	−30.59	−30.59	−30.59	−30.59	−30.59	−30.59
Box Open	Total	Meas	0.00	4.76	9.88	14.80	20.21	25.12	29.30	34.22	39.13	43.92	49.24	52.90	55.62	56.62
	Atten.	Adj	0.00	4.76	9.88	14.80	20.21	25.12	29.31	34.24	39.20	44.13	50.01	54.97	61.00	66.38
	dBSPL	Meas	0.00	−4.74	−1.19	−1.33	1.06	0.46	−2.32	−2.23	−2.17	−2.41	−1.52	−3.82	−7.30	−12.90
	Error %	Adj	0.00	−4.74	−1.19	−1.33	1.07	0.47	−2.30	−2.17	−2.00	−1.93	0.03	−0.05	1.67	2.12

^aWith no signal applied, the inherent measurement system noise floor is measured with microphone inside the sound field isolation box and room-under-test ambient level is measured with microphone outside the isolation box. Measured and noise adjusted attenuator performance is also shown in bottom section of the table for Box Open/Closed conditions. The linearity of the test signal injection system is demonstrated by noting Test Signal mVRMS drive levels [II(a)] versus Box Open/Adj result values [II(b)].

FIG. 4. Measured and inherent noise adjusted results for the test signal attenuation series under the box open/box closed conditions. The test signal is broadband noise and the measurement bandwidth is $\frac{1}{3}$ octave centered at 1 kHz. The thin dashed lines with dots indicate measured values tapering off to the indicated measurement system inherent noise floor. The thin solid lines display the noise adjusted corresponding values. The measured and noise adjusted ambient room levels are shown at -10.62 and -30.59 dB SPL. The displayed linearity below the measurement noise floor of noise adjusted results indicates inherent noise adjustment technique improves measurement accuracy near the noise floor and can precisely extend the measurement range up to 20 dB below the noise floor. The acoustic test signal level is approximately -31.47 dB SPL (0.534 uPa) when it reaches the noise adjusted ambient room level of -30.59 dB SPL.

MaxDiffDB). The actual measured values and corresponding noise adjusted values are plotted for both Box-Open and Box-Closed conditions.

A. Discussion of results

The acoustic verification method for the inherent noise adjustment technique steps linearly from 0 dBV to -65 dBV (1.0 VRMS to 0.56 mVRMS) in the Box-Open condition of Fig. 4. Continuing on in the Box-Closed condition, the noise adjusted attenuation is fairly linear until it clips at the adjusted room ambient level. Again, the actual room ambient noise level may be even less than -30.59 dB SPL, below the range of the adjustment algorithm. Had the adjusted measured ambient noise level stabilized above the adjusted inherent noise floor, the actual room noise would be indicated. Both conditions demonstrate that the adjustment technique improves the accuracy of measurements in the 1 kHz $\frac{1}{3}$ octave band as level diminishes to the noise floor and accurately extends the acoustic measurement system dynamic range to 20 dB below the system noise floor.

In Sec. IV, these methods are applied to establish generalized ambient noise specifications for a very quiet room suitable for publications in which it is important to accurately specify the characteristics of the room.

IV. METHODS: APPLICATION OF INHERENT NOISE ADJUSTMENT TECHNIQUE

This section describes an application of the inherent noise adjustment and verification technique to the problem of specifying the ambient noise level in an extremely quiet environment; in this case an anechoic chamber used for acoustical testing purposes. The performance analysis of the

results will be extended to full hearing frequency range to objectively document ambient noise specification of rooms in which human hearing testing at the threshold level might be considered. Assuming the unadjusted measurement system noise floor does not exceed the actual, true room ambient level by MaxDiffDB, the inherent noise adjustment technique should directly and accurately indicate the true ambient noise floor. As before in the 1 kHz narrow bandwidth investigation, the verification methodology was used to investigate the reliability of the measurement technique.

To explore the impact of various inherent measurement system noise levels, three different measurement data sets were collected simultaneously using three microphone/pre-amp combinations with high, medium, and low inherent noise characteristics. To explore the effect of measurement system bandwidth, data sets were analyzed using: full (20 – 20 kHz), wide (200 – 20 kHz), and narrow (1 kHz) $\frac{1}{3}$ octave bandwidths.

The basic application data acquisition methods were similar to above: (1) establish inherent measurement system noise floor levels for each instrumentation configuration, (2) collect measurements simultaneously at the same test signal attenuation level on all three systems, (3) adjust measurements for inherent noise effects on measurement system accuracy. Post-acquisition analysis performed at $\frac{1}{3}$ octave band intervals over full, wide, and narrow bandwidths permitted the investigation of frequency bandwidth effects on reported A-weighted loudness figures for the room under test.

V. RESULTS: APPLICATION OF INHERENT NOISE ADJUSTMENT TECHNIQUE

The “raw” measured and adjusted measured values for the three measurement systems are presented in both a

TABLE III. Acoustic test signal conditions (a) with measured (raw) and calculated (adjusted) inherent noise adjusted results (b) for low, medium, and high noise floor measurement systems.

(a)																		
Acoustic Test Signal Conditions																		
Test Signal At Generator	Signal Off		Box Closed, Signal On, Test Signal Level Applied to Loudspeaker, dBV															
			0	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50	−55	−60	−65		
	mVRMS																	
		Inh. NF	Amb. Lev.	1000	562	316	178	100	56.2	31.6	17.8	10.0	5.62	3.16	1.78	1.00	0.56	
Pink-Filtered Random Noise 1 VRMS (0 dBV) ~50 dBSPL	Test Signal Atten. Set	Mic inside box	Mic outside box	5		5		5		5		5		5		5		
					10	10		20	10		10	10		10	10			
						20		20				20	20		20	20		
								30	30	30	30	30	30	30	30	30		
(b)																		
Measured and Inherent Noise Adjusted Results																		
Sys. NF	$\frac{1}{3}$ Oct. Span	Result Type	Measured (Meas) and Inherent Noise Adjusted (Adj) Results, dBA															
Low ^b	20 Hz	Meas	5.65	6.75	27.48	23.61	19.07	14.71	10.58	8.43	7.52	7.04	6.84	6.91	6.87	6.86	6.79	6.81
	20kHz	Adj		0.47	27.46	23.54	18.87	14.13	8.92	5.23	3.05	1.58	0.88	1.12	0.99	0.94	0.64	0.71
	200 Hz	Meas	5.64	5.69	27.47	23.59	19.01	14.54	10.14	7.72	6.62	6.00	5.78	5.72	5.68	5.69	5.68	5.69
	20kHz	Adj		−10.06	23.59	23.52	18.80	13.94	8.25	3.59	−0.15	−4.30	−7.34	−9.11	−9.96	−10.01	−10.15	−9.96
	1 kHz	Meas	−10.59	−10.62	3.70	−0.68	−5.05	−7.94	−9.72	−10.27	−10.53	−10.60	−10.61	−10.65	−10.65	−10.65	−10.66	−10.62
		Adj		−30.59	3.53	−1.15	−6.47	−11.34	−17.14	−21.78	−27.11	−30.59	−30.59	−30.59	−30.59	−30.59	−30.59	−30.59
Med ^c	20 Hz	Meas	16.29	16.42	27.38	23.91	20.49	18.20	16.97	16.61	16.50	16.45	16.42	16.44	16.43	16.43	16.43	16.43
	20kHz	Adj		2.22	27.03	23.09	18.42	13.75	8.76	5.58	3.95	2.95	2.51	2.67	2.55	2.56	2.34	2.39
	200 Hz	Meas	16.29	16.30	27.37	23.88	20.43	18.11	16.85	16.49	16.37	16.32	16.30	16.30	16.30	16.30	16.30	16.30
	20kHz	Adj		−2.82	27.01	23.06	18.34	13.51	7.96	3.86	1.09	−1.26	−2.27	−2.75	−2.88	−2.89	−2.93	−2.88
	1 kHz	Meas	0.62	0.58	4.43	2.33	1.25	0.78	0.65	0.65	0.65	0.59	0.59	0.60	0.55	0.58	0.60	0.56
		Adj		−19.43	2.13	−2.46	−7.18	−12.44	−18.22	−19.38	−19.43	−19.43	−19.43	−19.43	−19.43	−19.43	−19.43	−19.43
High ^d	20 Hz	Meas	23.86	23.88	28.95	26.63	25.02	24.27	23.99	23.91	23.89	23.89	23.88	23.88	23.88	23.87	23.87	23.87
	20kHz	Adj		5.71	27.35	23.40	18.79	14.28	9.88	7.57	6.52	5.95	5.73	5.87	5.78	5.69	5.72	5.66
	200 Hz	Meas	23.85	23.86	28.94	26.61	24.99	24.25	23.96	23.89	23.86	23.86	23.85	23.85	23.85	23.85	23.84	23.85
	20kHz	Adj		4.19	27.34	23.37	18.72	14.08	9.31	6.62	5.27	4.47	4.19	4.19	4.07	3.99	4.12	4.04
	1 kHz	Meas	7.90	7.89	8.92	8.29	8.03	7.94	7.92	7.91	7.91	7.93	7.89	7.93	7.90	7.89	7.90	7.92
		Adj		−12.10	2.11	−2.35	−7.23	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10	−12.10

^aTo maintain high signal-to-noise ratio, series attenuators are used to control the test signal acoustic output level. With no signal applied, the inherent measurement system noise is measured with microphone inside the sound attenuating box and room-under-test ambient noise is measured with microphone outside the box. Cells containing results in boldface type indicate when decreasing adjusted measurement results “bottom out” by clipping due to either room noise or adjusted measurement system noise floor.

^bBrüel & Kjær 4955 $\frac{1}{2}$ in. low-noise.

^cBrüel & Kjær 4189 $\frac{1}{2}$ in. free-field.

^dBrüel & Kjær 4191 $\frac{1}{2}$ in. free-field microphone. Pulse signal analyzer, Lab Shop v16.

tabular A-weighted view and a graphical selected test signal level, frequency dependent view. Effects of measurement analysis bandwidth are also included.

A. Measured and inherent noise adjusted results, A-weighted (dBA) levels versus test signal level

Overall testing conditions and summary results presented in dBA for each test signal condition, for each noise floor, across three different bandwidths, are displayed in Table III. The inherent system noise floor measured for each microphone and bandwidth condition is shown in the “Inh. NF” column. The measured and noise adjusted test room ambient level result is shown in the “Amb. Lev.” column. The remaining columns display each microphone’s measured and noise adjusted results for each test signal level for the various bandwidth conditions.

As expected, the inherent noise floor varies across measurement systems and increases as measurement bandwidth widens. The results are reported in boldface type when it is apparent the limits of the inherent noise adjustment technique have been reached. If decreasing adjusted measured values stabilize above the inherent noise floor of the measurement system, the inherent noise adjusted measurement value is equivalent to the true ambient room level. If decreasing adjusted measured values descend to the inherent noise floor of the measurement system, the true room ambient level is below the measurement noise floor. The former condition is only valid in the low noise/full bandwidth condition. In every other condition, the true ambient room level is less than adjusted measurement system noise floor. A simplified guide to measurement procedure and interpretation of results is shown as a flowchart diagram in Fig. 5.

FIG. 5. Guide to measurement procedure and interpretation of results.

FIG. 6. Plots of actual measured and inherent noise floor adjusted results and calculated noise adjusted results for low-noise measurement system. The corresponding calculated noise adjusted plot for each of the measured results for test signal levels of 20, 10, 0, -10, and -20 dB SPL and the off ("ambient") condition are shown. Low frequency results below 160 Hz are dominated by test room modes. Results at frequencies >10 kHz and at frequencies less 125 Hz are distorted and limited by poor acoustic stimulus transducer sensitivity at extreme frequency ranges. Adjusted ambient level is dominated by maximum difference parameter setting of 20 dB. Similarities in waveform morphology at decreasing test signal levels indicates sensitivity of subtractive energy based, inherent noise adjustment method.

B. Measured and inherent noise adjusted results, Sound pressure level (dB SPL) versus frequency band

Figure 6 plots selected test signal level $\frac{1}{3}$ octave band dBSPL results for each noise floor and box open/closed condition. The corresponding test signal levels displayed in each box open/closed and noise floor group are noted on the right side of Figs. 6(A), 6(B), and 6(C). The uppermost, thinly dashed trace in each group of waveforms is a measured result, the remaining traces are inherent noise adjusted results. The $\frac{1}{3}$ octave band inherent measurement system noise floors are shown as large dotted lines, duplicated on box open/closed plots in Figs. 6(A), 6(B), and 6(C). The

measured and noise adjusted ambient levels for each noise floor condition are plotted in wide gray lines for each box open/closed condition on Figs. 6(A), 6(B), and 6(C). It is probable that poor transducer performance at both high and low frequency range extremes, as well as low frequency room characteristics such as acoustic modes contribute to limited measurement and adjustment range in the low frequency bands.

Figure 7 displays a close-up view of how the noise adjustment technique operates on measured signals near the inherent measurement system noise floor. For each trace set, the dashed lines display the measured values and the solid lines represent the corresponding noise adjusted values. The

FIG. 7. Similar to Fig. 6, but at increased amplitude resolution, a view of frequency response plots of actual measured and inherent noise floor measured results and calculated noise adjusted results for low-noise measurement system for test signal levels of 30, 20, 10, 0, -10, and -20 dB SPL and the off ("ambient") condition are shown. The -20 dB set illustrates diminishing sensitivity at test signal levels approaching 20 dB less the inherent levels. At frequencies <160 Hz, the room acoustic behavior appears to swamp out changes in room level change due to signal level changes. This results in tapering off of dBA measurements into the noise floor as signal level drops in amplitude instead of linear stepping. Increased attenuation of upper frequencies by the isolation box causes rapid high frequency amplitude roll-off.

traces displaying measured values flatten out as they approach and descend into the noise floor. The noise adjustment waveforms maintain good symmetry near and below the system noise floor except at the lower and upper frequency ranges indicating accurate and reliable operation of the adjustment procedure. The effectiveness is most readily seen in Fig. 6(A). Decreases in test signal level are swamped by room noise in the lower frequency bands. At the upper frequency band, particularly in Fig. 6(B), the already low transducer acoustic output level is further truncated by increased isolation box attenuation at upper frequencies.

Figure 8 shows overall A-weighted measured and adjusted measured results for all measurement system, test signal level, and analysis bandwidth conditions. For the same test room, there are significantly different measured and adjusted measured ambient noise as depicted by wide gray dashed and solid horizontal lines on each plot. The effects of measurement bandwidth in our real-world room test case are demonstrated in all three measurement system result sets. Non-linear plots at the low test signal levels demonstrate the effect the room frequency anomalies have on the A-weighted room levels since the level of low frequency

FIG. 8. (A)–(I) A-weighted measured and adjusted measured results for low, medium, and high noise floor systems; each analyzed under full, wide, and narrow bandwidth and Box Open/Closed conditions for test signal levels from 0 to -65 dBV. Measured and inherent noise adjusted ambient room noise is shown on each plot and varies depending on system noise floor and analysis bandwidth. When there is no longer a linear relationship between the test signal drop in amplitude and adjusted ambient level, either the inherent noise floor or true ambient room level has been reached.

band activity is fairly constant regardless of test signal level. At higher test signal levels, this effect is masked or swamped out by the dominating upper frequency energy levels.

The test room has demonstrated low frequency acoustical behavior anomalies whose exact cause remains undetermined (Ellingson and Bock, 2013). It is not unusual to have difficulty measuring pure tones at frequencies <200 Hz in rooms: ISO (2003) notes that frequencies less than 250 Hz can introduce measurement uncertainty, and Jacobsen and Molaes (2009) note substantial uncertainty in low frequency sound power measurement in rooms under certain conditions.

C. Discussion of results

A summary of measured and adjusted measured results obtained using the three measurements system noise floors and three different $\frac{1}{3}$ octave analysis frequency spans is contained in Table IV. First of all, the measured inherent system noise floor, measured (raw) ambient room noise, and adjusted ambient room noise are repeated from Table II. The next column displays the inherent noise adjustment algorithm difference between raw and noise adjusted measurement values. In the 1 kHz case, since the amount of adjustment is at the MaxDiffdB point, the actual room noise at 1 kHz is even lower than any adjusted ambient value. In both wider bandwidth span conditions, all adjustment amounts are within the 20 dB range of the algorithm. For reference purposes, the next column displays the test signal level when the adjusted measured result for that particular system and bandwidth stops decreasing in amplitude. The next column contains comments about room noise impacts: are they a factor at this bandwidth span, and noise floor; is the measurement system noise floor causing measurement error?

The last two columns tabulate measurement relative error using the various measurement systems and analysis bandwidths. Since the low noise floor system had the most sensitive result at the 200–20 kHz bandwidth where room noise was not below the measurement system noise floor, it is assigned to be raw references R1, R2, and R3, and adjusted references A1, A2, and A3. The difference between raw measurement values and corresponding bandwidth span adjusted reference values is shown in the raw measurements column. The raw measurement error indicates how “far off” a measurement would be from its “real actual” value if the inherent noise adjustment methodology was not applied to the raw measurement. As shown, the error in ambient room measurement results ranges from 6.28 dBA to nearly 40 dBA.

Finally, the last column displays the adjusted measurement error for the ambient room measurement results. This is the measurement error after applying the inherent noise adjustment technique to raw measured values. The error ranges from 0.0 dBA to 5.24 dBA in the 20–20 kHz condition where low frequency room noise is dominating, to 0.0 dBA to 14.25 dBA in the 200–20 kHz condition where measurement system noise floor dominates, to no more than 0.0 dBA to 18.49 dBA in the narrow bandwidth case when the

TABLE IV. Summary of room ambient noise measurement results shown in Table III. All results reported in dBA.

$\frac{1}{3}$ Oct. Span	NF of Meas. System	Meas. Inh. NF	Meas. Raw Ambient Room Noise (C4)	Adj. Ambient Room Noise (C5)	Amount of Adj. (C4–C5)	Signal Level when Adj. range runs out ^a	Room noise impact on meas.	Comments	Raw meas. error	Adj. meas. error
20 Hz 20 kHz	Low	5.65	6.75 (R1)	0.47 (A1)	6.28	–39.53	High Low	Adj. meas. results dependent on meas. system bandwidth as well as NF. A1 is accurate.	6.28 (R1–A1)	0.0 (R1–R1)
	Med	16.29	16.42	2.22	14.20	–37.78	frequency room noise dominates at low signal levels.		15.95 (C4–A1)	1.75 (C5–R1)
	High	23.86	23.88	5.71	18.17	–27.65			23.41 (C4–A1)	5.24 (C5–R1)
200 Hz 20 kHz	Low	5.64	5.69 (R2)	–10.06 (A2)	15.75	–31.41	Low	Adj. meas. results dependent on meas. system NF. A2 is accurate.	15.75 (R2–A2)	0.0 (R2–R2)
	Med	16.29	16.30	–2.82	19.12	–22.99			26.36 (C4–A2)	7.24 (C5–R2)
	High	23.85	23.86	4.19	19.67	–12.66			33.92 (C4–A2)	14.25 (C5–R2)
1 kHz	Low	–10.59	–10.62 (R3)	–30.59 (A3)	19.97	–31.47	None	Adj. meas. range exceeded on all systems.	>19.97 >(R3–A3)	>0.00 >(R3–R3)
	Med	0.62	0.58	–19.43	20.01	–27.87		Room noise @ 1 kHz < –0.59.	>31.17 >(C4–A3)	>11.16 >(C5–R3)
	High	7.90	7.89	–12.10	19.99	–12.89		System bandwidth is not a factor.	>38.48 >(C4–A3)	>18.49 >(C5–R3)

^aDerived from Table III. Box Closed/Signal On/0dBV condition Adj Result value less attenuation setting when Adj result diminishes to Adj ambient room level.

TABLE V. Test room ambient noise specification based upon performance measurements obtained for this study.

Room	NCRAR P5-161A	Operator	RME
Date	May 5, 2013	Temp., deg F	70
Equipment	B&K 4955, Pulse LAN-XI, Fonix isolation box.	Humidity, %	35
Notes	Full test with verification at 5 dB steps.	Ventilation, CFM	325

Test room ambient noise measurement results, dBA except where noted.					
$\frac{1}{3}$ Oct. span	Meas. inherent noise floor	Meas. ambient level	Inherent noise adjusted ambient level	Injected test signal verified	Notes
20 Hz	5.65	6.75	0.47	Yes	True room ambient level = 0.47.
20 kHz					
200 Hz	5.64	5.69	-10.06	Yes	True room ambient level = -10.06.
20 kHz					
1 kHz	-10.59	-10.62	-30.59	Yes	True room ambient level $\leq$ -30.59.

actual room noise is below the measurement system noise floors of all systems.

What is the actual ambient noise level of the room under test? From the data sets and analysis shown here, the answer is related to the analysis bandwidth and measurement system noise floor. Table V reports the ambient noise levels in this study's test room in a format containing both measurement bandwidth and system noise floor information. The report format contains information to help establish the credibility of reported ambient noise measurements and would be more informative than simply publishing a singular ambient noise figure. It might also be relevant to consider the room frequency response and how it affects the experiments to be undertaken in the room. Similarly, if an application has a limited set of frequencies or bandwidths present in the signals being measured, then it would be sufficient to characterize the room only in the frequency regions containing stimulus energy. For example, if a room resonates at 160 Hz creating a standing wave energy pattern but the lowest stimulus frequency used in a study is 500 Hz, then one might reasonably specify an ambient analysis lower limit of 500 Hz less one $\frac{1}{3}$ octave step (i.e., 315 Hz) when recording true room ambient noise level. In certain applications, it might be useful to evaluate room noise at many more narrow band frequencies, possibly even at every fractional octave band to fully characterize test room performance.

VI. CONCLUSION

This work extends ambient noise measurement work done in the 1970s based upon the subtractive energy method. It models and demonstrates an implementation of the subtractive noise method, called the inherent noise adjustment technique, improving signal measurement accuracy above and below the measurement system noise floor. It contributes a new verification technique shown effective to demonstrate the accuracy of the inherent noise adjustment methodology in a real-world test room. The results obtained using the verification method indicate that accurate investigation of acoustic signal frequency and level behavior at sound pressure levels below the noise floor of measurement systems is

feasible. The tool also improves accuracy of measurements obtained near but above the noise floor.

Some facilities might regularly document a room's ambient noise level to ensure room noise has not increased due to inaudible sources such as wall-wart power supplies, light bulbs, or other newly added mechanical or electrical devices. Once the test room low-level ambient noise level has been established, the verification technique might not be necessary every time ambient room levels are measured. If the measured and verified ambient room level is greater than the inherent noise floor of the measurement system, a future increase in room noise will be detectable without the verification step.

The interest here has been stationary noise, investigated using test signals of wide-band random character. Applying the methods to investigate very low level, stationary in frequency, pure tone target measurements has not been investigated here. Consideration of frequency or room position dependencies in room sound pressure level which might be related to room size, shape, and nodal behavior as discussed by Jacobsen and Molaes (2009) is beyond the scope of this paper but it is possible the methods described here could be useful to study the effects of these parameters.

The results and analysis shown here demonstrate the importance of properly specifying measurement bandwidth and selecting measurement equipment with appropriate inherent noise floor when documenting stationary test signals in rooms with very low ambient noise characteristics or in environments dominated by low frequency inherent room behavior. In some cases, it might be useful to create an array of narrow band ambient noise measurements, possibly at every fractional octave interval.

Relying upon indirect methods to specify room ambient noise could be highly inaccurate. For example, using structural insulation properties to mitigate external noise source intrusion might be meaningless if a noise source is present inside the room itself or if frequency dependent modal characteristics of the room created low-level acoustic energy. Applying the inherent noise adjustment technique, and if necessary, the noise injection verification technique described in this article could improve low-level signal measurement accuracy and help objectify the publication of

results. These direct methods demonstrate measurement range can be reliably extended near and below the measurement system noise floor. The techniques also support precisely investigating frequency dependent behavior of low room ambient levels.

It has been suggested the subtractive energy technique could be applicable in other measurement environments or possibly of use when measuring small electrical energy. If so, the inherent noise adjustment and verification techniques described here might be again be useful to improve low-level signal measurement accuracy or to study bandwidth related characteristics.

Compared to methods published in the 1970s, modern equipment that combines acoustical transduction, pre-amplification, filtering, data acquisition, storage, and frequency band analysis make working in this area far simpler. However these techniques also could be undertaken with modern modular instrumentation including microphones, preamps, digitizers such as high quality PC-based sound cards, and general purpose scientific software environments.

If necessary, the adopter of these methods could improve verification instrumentation in at least two areas. The attenuation chain and amplifier coupling could be redesigned to be of balanced, rather than single-ended design to improve signal-to-noise ratios. This could extend the attenuation range in some circumstances to eliminate the need for the box-open/box-closed conditions. The attenuation components could be more precisely selected to further reduce test signal attenuation error, in particular, at the 5 dB step. A test signal transducer with improved bandwidth characteristics could be used to examine low and/or high frequency room performance more precisely.

When performing verification testing in extremely quiet rooms with very low levels of test signal presentation, it might be possible to replace the transducer-in-box/Box-closed scheme with an insert earphone type transducer operating in free air. Although acoustic directivity and frequency response might need additional consideration, the expected overall downward shift in the dynamic range of the acoustical output level might better match the room conditions. This could eliminate the need to maintain S/N ratios via loudspeaker placement in a box, which would simplify measurement procedure.

It appears the test room used for this study has resonances exhibiting large standing wave energy at low frequencies as shown in microphone traversal measurements (Ellingson and Bock, 2013), hence swamping wide-band noise figure measurements. This is a problem with the test room, not the measurement technique. Combining the measurement and verification techniques shown here with traversing microphone apparatus could help in documenting these types of room characteristic behaviors.

It might not be necessary to emit the verification test signal from inside an isolation box, but problems can occur if one outstrips the attenuation range resulting in poor signal-to-noise ratio or signal level drops below the minimum sensitivity of the transducer. It is possible an insulating transducer box would not be necessary if room ambient energy level exceeds the transducer sensitivity by MaxDiffDB.

However, an isolation box might be still be necessary to establish the inherent noise floor of the measurement system.

Regardless of whether the reader actually conducts the experiments described in this article, the considerations described above can serve as a reference for those interested in measuring very low-level signals and identifies conditions that can cause measurement errors. In summary, it is indeed possible to measure ambient noise below the noise floor of the measurement system, provided that an appropriate series of operations is used to adjust and validate the measurements.

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¹Throughout this paper all dB sound pressure level (SPL) and dBA unit values are relative to 20 μ Pa, which is the designated threshold of human hearing, 0 dB = 20 μ Pa. The term, level, when used generally, will refer to dB relative to that reference level.

²Basic formula for summing incoherent SPLs in dB: $L_S = 10 \log_{10} (10^{L_1/10} + 10^{L_2/10})$. For example, $10 \log_{10} (10^{20\text{dB}/10} + 10^{0\text{dB}/10}) = 20.043\text{dB}$. Useful online energy calculation tools can be found at Universität der Künste Berlin (2013).

³MinDiffDB was set to 0.05 for the analysis results presented in this paper. In hindsight, a MinDiffDB value of 0.043 should have been used with a MaxDiffDB value of 20 dB since the decibel addition of -20 dB and 0 dB = 0.043 dB. The impact of this error will be limited to any measured values happening to exactly fall in the 0.007 dB range between of $I + 0.043\text{ dB}$ and $I + 0.050\text{ dB}$. Using the verification techniques at 5 dB step sizes as described in this study, the worst case impact on any inherent noise adjusted result would be 0.05 dB at one attenuation step with the odds of a measurement landing exactly within the narrow 0.007 dB error range seemingly quite small. For future measurements MinDiffDB should get set to the decibel sum of -MaxDiffDB and 0 dB.

⁴Preliminary testing was performed with box open and a wider attenuation range, 0 to 90 dB in 10 dB steps. Results showed S/N and transducer drive problems when exceeding 65 dB of attenuation. Also 10 dB step sizing was not adequate to smoothly verify performance at very low test signal levels. Results reported here used box open/closed and 0 to 65 dB attenuation range in 5 dB steps.

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