COMPARING MEASURED SOUND STRENGTH TO THEORY AS A FUNCTION OF REVERBERATION TIME AND ROOM VOLUME

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1 INTRODUCTION

ISO Standard 23591 demonstrates how the sound pressure level in a room may be estimated with a knowledge of (1) the sound power of sources in that room and (2) the sound strength G of that room as defined in ISO 3382-1. In this paper, the theory connecting room volume V, reverberation time T_{60}, and sound strength G is summarized, and a comparison of measured G to this theory is explored for a wide range of rooms. In addition to an explanation of the mathematical model, a description of the calibration of measurement equipment using Odeon software is discussed. A brief review of the rooms in which sound strength was measured is provided. Both measured and theoretical sound strength results are presented for the rooms reviewed. The difference between measured G and theoretical G using this mathematical model is analyzed statistically both for this test setup and with concert hall data from Beranek's book. This model lends itself to designing rooms of appropriate reverberance and loudness for a given context, musical or otherwise.

2 RELEVANT PAST RESEARCH ON SOUND STRENGTH (G)

Sound Strength G can be thought of as the "gain" of the room, i.e. how many decibels the various room reflections cumulatively amplify the direct sound. Despite extensive reference to the acoustical parameter G in the literature, only recently has it seen a novel application to rooms for music. For this method, the sound power of musical instruments based on measurements are summed to identify an appropriate G goal tailored to a particular ensemble. This method is described in Annex A of the ISO-23591 standard[1], and other papers[2,3] by Rindel. A brief history of reverberation time (RT) goals is discussed leading up to Rindel's work on how G relates to RT, which is the foundation of this paper.

It is common for acoustic consultants to design a room based on a target reverberation time. A vast amount of architectural acoustics literature covers reverberation time goals for different room types. Sabine himself provides his empirical results of what reverberation times are preferred in 1902[4], as did Bagenal in England in 1933[5]. Watson proposes a scaling of reverberation time with room volume in 1923[6]. Textbooks written by various authors including Barron[7] and Egan[8] provide similar RT goals. While some will mention loudness as an important aspect (indeed, it is often forgotten that Sabine himself states loudness as a coequal parameter to reverberation in his essay, *Reverberation*[4]), it seems often to be considered separately from reverberation time, if at all.

Beranek noted that "little attention has been paid to the strength of sound G as an acoustical parameter for evaluating the performance of concert halls" in part because it is simply SPL with a different reference. Beranek continues that the industry has ignored the tested fact that for rooms of different reverberation times, if G is equal, perceived loudness is nearly equal[9]. Beranek claims that "there is no evidence in the literature" that G calculated with $S\bar{\alpha}$ from Sabine's equation matches measurements of G_{Mid} in halls. He then evaluates whether this could work in the paper. However, it is worth noting that Beranek always keeps $S\bar{\alpha}$ present in the equations he uses. It will be seen later that the interesting relationship of this paper can be gleaned if $S\bar{\alpha}$ is mathematically substituted. Beranek's contribution through his paper[9] therefore appears to be showing that high correlation (*0.97*) can be found between his G_{Mid} measured and his G_{Mid} calculated based on the Sabine equation.

In recent decades, G has enjoyed greater attention: Katz notes that G and its derivatives have "been found to be highly perceptually relevant"[10]. Some acoustic consultants have increasingly noticed that you can "over-drive" or "overpower" a room that is volumetrically too small, and/or too reverberant. This has led to some rule-of-thumb guidelines: Adams et al. state[11] that Arup has used Equation 1 in the design of rehearsal rooms for symphonic orchestras to prevent excessive loudness:

$$10\log(S\bar{\alpha}) - 6\ dB > 21\ dB \qquad (1)$$

This relationship gets at the problem at hand yet does not establish the origins of the equation from first principles.

Rindel proposes a method[2] of calculating the appropriate sound strength G for a room based on the anticipated sound power of sources in the room, that was developed into the Norwegian standard NS-8178[12], and later adopted as part of ISO 23591[1]. Various goals of RT as a function of volume have been proposed within ISO 23591 plotted over the equal-G curves in that standard[1].

Rindel's method is already being used in design, at least for student projects. Nijs and DeVries demonstrate the application of the method[13], but plotting the results on $G-RT$ diagrams, and comparing to target values for G and $T60$ by Barron[7] and Beranek[14]. An apt description from their paper is "Many students of our faculty want to have Mahler's 8th symphony played in a local gymnasium with a 3200 m^3 volume by choosing a 2.1 second reverberation time. Figure 1 shows them why this sounds like an inferno: it is much too loud."[13]

This paper is focused directly on exploring Rindel's method mathematically and empirically. The details of the process will be reviewed and built upon in section 4. The author notes that this method appears to be a powerful design tool for the acoustic consultant in the design of rooms, yet relevant equations that logically follow from the process are notably absent from ISO 23591.

Skålevik elaborates[15] on Rindel's work, noting that, despite the useful nature of research about instrument sound power, it is not yet fully understood what the right goals perceptually are: Rindel assumes mean forte levels[2], but is that the correct assumption? Skålevik identifies that "it remains to settle which forte levels actually are the preferred ones, whether the preferred forte level from a flute is the same as the preferred forte level from a trombone, and so on. Once the statistics for such preferred values are established, one would have reached a perceptually based criterion that links a $V-T$ combination to a certain G value. But today this is a missing link."

Based on the above, the author believes a small lapse in the research can be filled by demonstrating the mathematical model suggested in ISO 23591 in greater detail than is presented in that standard. While it is assumed that rooms are already being designed by this method in Norway and other European countries due to the standards listed[12,1], the author is not currently aware of any extensive study comparing Rindel's method to measurements of real rooms. So, it is hoped that through the author's field measurements of rooms, higher empirical confidence in the model can be achieved, preparing the way for others to find Skålevik's "missing link"[15] through further perceptual studies.

3 MEASURMENT SETUP

To verify the mathematical relationships proposed by Rindel[2] and now formalized in ISO-23591:2021[1], impulse response (IR) measurements of many rooms were taken.

In the current investigation a QSources Qoms2 monopole omni-directional source was used. The speaker is omnidirectional[16] according to ISO 3382-1[17] per QSources' measured directivity plots.
The measurement signal was a swept sinusoid with sampling frequency of 44.1 kHz generated through Odeon software on a Dell laptop. Impulse responses were measured with a Zoom H3-VR audio recorder 4-channel ambisonics mic at ear height of an average listener: 4.55 ft. The mic

employs first-order ambisonics, and the FuMa setting was used. Only the W (omni) channel of the B-Format output is used for monaural analysis, and it is scaled by √2 (amplified by 3 dB) to account for the FuMa coding convention, per correspondence with Odeon.

Despite its acknowledged importance, Katz notes[10] that many acoustic consultants are not measuring G because it is "too difficult to measure by many practitioners". The various acoustical software packages do offer methods of calculating and/or measuring G with the software. Odeon software has published a process[18] by which a practitioner can calibrate the entire signal chain of their test equipment relative to a reverberation chamber or to an anechoic chamber. In the author's case, Odeon software was used with the above equipment with the goal of calibrating the signal chain in the NWAA Labs reverberation chamber in Elma, WA. While an initial calibration attempt was made, some challenges precluded using the G results obtained, though RT's were deemed acceptable.

Further details about the author's measurement methods after the unsuccessful initial calibration attempt are described in section 6, including a "work-around" simplified in-situ method of obtaining G based on the work of Hak et al.[19]

Table 1 summarizes the rooms measured. The room volume is in cubic feet and the mid-frequency reverberation time $T30_{Mid}$ is provided, averaged over the positions of the Odeon IR measurements.

Table 1: Basic measures for the evaluated rooms.

Abbreviation	**Description**	**Volume (CF)**	**Volume (m^3)**	$\boldsymbol{T30}\ (s)$
O	Office	1,455	41	0.4
MA	Meeting Room A	2,899	82	0.5
MB	Meeting Room B	2,930	83	0.5
MC	Meeting Room C	2,986	85	0.5
FRC	Fitness Room - with ACT [a]	3,618	102	1.2
CA	Conference Room A	4,654	132	0.4
CB	Conference Room B	5,500	156	0.6
MD	Meeting Room D	6,622	188	0.5
FRE	Fitness Room - Exposed [a]	7,004	198	1.3
EM	Elementary Music Classroom	8,532	242	0.7
LR	Studio Live Room	9,335	264	0.5
PR	Percussion Room	9,350	265	0.6
CH1	Court House Position 1 [b]	11,687	331	1.2
CH2	Court House Position 2 [b]	11,687	331	1.2
BR1	Band Room	26,439	749	0.7
BR2R	Band Room (Curtains Retracted) [c]	37,939	1,074	0.6

BR2E	Band Room (Curtains Extended) [c]	37,939	1,074	0.5
EG	Elementary School Gym	59,523	1,686	1.2
S	Sanctuary	87,025	2,464	1.9
RH	Recital Hall	114,320	3,237	0.9

[a] The Fitness Room is measured with acoustical ceiling tile (ACT) at 9.1' and exposed to structure with the deck at 17.6'.
[b] The courtroom is measured in the same condition, but from two different source positions.
[c] The second band room is measured from the same locations in two curtain configurations.

4 THEORY

4.1 Derivation of Reverberation Time as a function of V and G

The mathematical relationship connecting sound strength to room volume and reverberation time is presented in ISO Standard 23591 as a graph (Figure A.1), with the method for logarithmically summing instrument sound powers described in Annex A of the same standard[1]. However, in what follows it is more useful to start with the derivation of the relationship more explicitly presented in an earlier paper by Rindel[3]. Rindel explains that the sound pressure level L_p in a room can be determined in the standard way as a combination of the direct and reverberant components (here Rindel references equation 3.43 from Maekawa et al.[20]):

$$\mathrm{L}_p = L_w + 10\log\left(\frac{1}{4\pi R^2} + \frac{4(1-\bar{\alpha})}{S\bar{\alpha}}\right) \tag{2}$$

Where L_w is the sound power of an omni-directional source, R is the source-receiver distance, S is the total room surface area and $\bar{\alpha}$ is the mean absorption coefficient of all room surfaces. Assuming the required 10-meter distance for R_0 the sound strength (G) can be represented mathematically here as:

$$G = 10\log\left(\frac{4(1-\bar{\alpha})}{S\bar{\alpha}}\right) - 10\log\left(\frac{1}{4\pi R_0^2}\right) \tag{3}$$

Where the distance term R from Equation 2 can be assumed to be a constant rather than a variable if the room is assumed to be diffuse[13]. Rindel then acknowledges that the room surface area is typically not known and must be estimated. A rectangular prism is assumed in the example given with volume V and ratio of length, width, and height of (1.6:1:0.8). This leads Rindel to an estimated surface area of:

$$S = 7.36\left(\frac{V}{1.28}\right)^{2/3} \cong 6.243161(V)^{2/3} \tag{4}$$

And a mean absorption coefficient of:

$$\bar{\alpha} = \frac{0.161V}{TS} \cong \frac{0.0258}{T}\sqrt[3]{V} \tag{5}$$

With reverberation time T and room volume V. To generalize this example, a surface area defined as a function of room Volume $S(V)$ is assumed by the author.
For a cuboid room, it follows that the surface area function is:

$$S(V) \cong 6\left(\sqrt[3]{V}\right)^2 \tag{6}$$

For a spherical room the surface area function is defined as:

$$S(V) = 4\pi\left(\sqrt[3]{\frac{3V}{4\pi}}\right)^2 \tag{7}$$

Rindel presents equal-strength curves plotted on a graph of reverberation time versus room volume in his earlier paper[2], a version of which is also included in ISO-23591[1]. Yet, the equations defining the equal-G sound strength curves are never analytically presented, instead expecting the reader to extract the values from the graph much as engineers used nomographs in the past.

What follows is the derivation of the equation that would generate the equal-G sound strength curves in Figure A.1 of ISO-23591[1], i.e. the reverberation time $T60$ defined as a function of room volume V and sound strength G. The Sabine-Franklin Equation[21] will be used, to retain a generalized form for the following algebraic manipulations:

$$T_{60} = \frac{4\ln 10^6}{cS\bar{\alpha}}V \tag{8}$$

Where c is the speed of sound and the natural logarithm $\ln 10^6$ acknowledges that $T60$ is defined as the drop to inaudibility equivalent to one millionth of the initial sound power of the source excitation, i.e. 60 decibels. With standard values of c = 1,125 ft/s or 343 m/s, this leads to the Customary Units coefficient of 0.049 s/ft or the S.I. coefficient of 0.161 s/m, respectively).

First, the Sabine Equation is rearranged, solving for the mean absorption coefficient:

$$\bar{\alpha} = \frac{4\ln 10^6}{cST_{60}}V \tag{9}$$

It is necessary to substitute the mean absorption coefficient thus obtained (equation 9) into *both* positions of $\bar{\alpha}$ in the equation for sound strength (Equation 3):

$$G = 10\log\left(\frac{4\left(1 - \frac{4\ln 10^6}{cST_{60}}V\right)}{S\left(\frac{4\ln 10^6}{cST_{60}}V\right)}\right) - 10\log\left(\frac{1}{4\pi R_0^2}\right) \tag{10}$$

Simplifying this expression, adding the 10-meter distance term to the left-hand side, and dividing by 10 yields:

$$\frac{G}{10} + \log\left(\frac{1}{4\pi R_0^2}\right) = \log\left(\frac{cT_{60}}{V\ln 10^6} - \frac{4}{S}\right) \tag{11}$$

At this point, the appropriate surface area function $S(V)$ is substituted into the right-hand side. The cuboid room surface area function will be assumed here (Equation 6), resulting in:

$$\frac{G}{10} + \log\left(\frac{1}{4\pi R_0^2}\right) = \log\left(\frac{cT_{60}}{V\ln 10^6} - \frac{4}{6\left(\sqrt[3]{V}\right)^2}\right) \tag{12}$$

Recall that the goal here is to isolate T_{60} as a function $t(V, G)$. Raise 10 to the power of the left and right sides of the equation:

$$10^{\left(\frac{G}{10}+\log\left(\frac{1}{4\pi R_0^2}\right)\right)} = \frac{cT_{60}}{V \ln 10^6} - \frac{4}{6\left(\sqrt[3]{V}\right)^2} \tag{13}$$

It now follows that the T_{60} reverberation time can be defined in terms of room volume V and sound strength G as:

$$T_{60} = \frac{V \ln 10^6}{c}\left(\frac{4}{6\left(\sqrt[3]{V}\right)^2} + \frac{10^{\frac{G}{10}}}{4\pi R_0^2}\right) \tag{14}$$

Note that all references to room surface area S and mean absorption coefficient $\bar{\alpha}$ have been eliminated. If R_0 is assumed to be 10 meters, per the definition of strength measurements in the ISO 3382-1 standard[17], and the locus of all points for $G = [5\,dB, 10\,dB, 15\,dB, 20\,dB, 25\,dB]$ over the domain $V = [10\,m^3 : 10{,}000\,m^3]$ is plotted, a graph equivalent to Figure A.1 in the ISO 23591 standard[1] is generated, see Figure 1. An example calculation is a room with a volume of $400\,m^3$ and a $G = 15\,dB$ yields a reverberation time of 0.6 seconds. If there were a difference between Eq. (14) and the graph, it would presumably be as a result of a different $S(V)$ assumption than Rindel and would only require doing a couple examples to calibrate what the assumed function is. However, it appears that the cuboid room matches the assumption made in the ISO 23591[1] graph in Figure A.1.

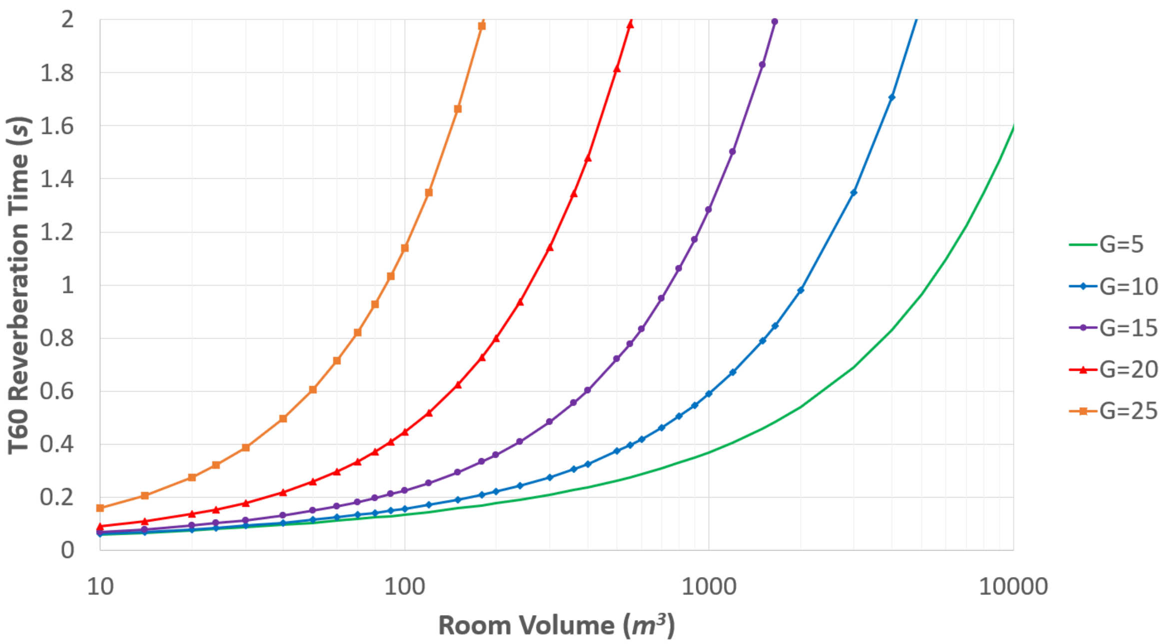

Figure 1: Equal-strength (G) curves generated by Equation 14 yield same graph as ISO 23591 Figure A.1.

Besides identifying the analytic expression used to plot Figure A.1, why is this important? In the case of renovation of an existing musical rehearsal or performance room with volume V meant to support an ensemble requiring sound strength G, The maximum reverberation time T_{60} can be calculated by the acoustic consultant that if not exceeded, will prevent excessive loudness of that ensemble within the room. While this is exactly what Figure A.1 plots, the author feels it was a notable omission to ISO 23591 to exclude the analytic expression (Equation 14), and the author recommends it be included in the next update of that standard. Then, if this does not match the measured $T60_{meas}$ in this room, the exact quantity of absorbing finishes can be determined to bring the room into agreement with the G appropriate for that ensemble.

4.2 Derivation of sound strength as a function of V and T60

The manipulations above led to the function $T_{60} = t(V, G)$, but it would have been more straightforward to make the relevant substitutions without solving for $T60$, which would lead to $G = g(V, T60)$. This equation is as follows:

$$G = 10\log\left[4\pi R_0^2\left(\frac{cT_{60}}{V\ln 10^6} - \frac{4}{6\left(\sqrt[3]{V}\right)^2}\right)\right] \tag{15}$$

This version of the relationship would likely be most useful in the case when the consultant is working on a facility with preservation requirements such that the room volume is fixed and no changes to finishes are allowed (i.e. changing $T60$ is unacceptable). While in such cases an electronic enhancement system is likely to be used, the option of last resort is an operational solution: use this version of the formula to calculate the maximum ensemble that can be supported in the room and encourage users to not exceed certain ensemble sizes and instrumentations.

4.3 Derivation of room volume as a function of G and T60

But perhaps the most useful form of the relationship for the consultant would be the function that solves for room volume $V = v(T_{60}, G)$. Starting from Equation 13, exponentiating the logarithm and rearranging the terms yields:

$$\frac{4}{6\left(\sqrt[3]{V}\right)^2} = \frac{cT_{60}}{V\ln 10^6} - 10^{\left(\frac{G}{10}\right)}\left(\frac{1}{4\pi R_0^2}\right) \tag{16}$$

Solving for V requires isolating the fractional power of V on one side of the equation and leaving non-fractional powers of V on the other side (in this case, the reciprocal of V to the first power). In this way, both sides can be raised to the appropriate power that will eliminate the fractional power, leaving only integer powers of V. For this case, that means cubing both sides of the equation:

$$\left(\frac{4}{6}\right)^3\frac{1}{V^2} = \left[\frac{cT_{60}}{V\ln 10^6} - 10^{\left(\frac{G}{10}\right)}\left(\frac{1}{4\pi R_0^2}\right)\right]^3 \tag{17}$$

Distributing the third power on the right side:

$$\left(\frac{4}{6}\right)^3\frac{1}{V^2} = \left(\frac{cT_{60}}{V\ln 10^6}\right)^3 + 3\left(\frac{cT_{60}}{V\ln 10^6}\right)^2\left[-10^{\left(\frac{G}{10}\right)}\left(\frac{1}{4\pi R_0^2}\right)\right] + 3\left(\frac{cT_{60}}{V\ln 10^6}\right)\left[-10^{\left(\frac{G}{10}\right)}\left(\frac{1}{4\pi R_0^2}\right)\right]^2 + \left[-10^{\left(\frac{G}{10}\right)}\left(\frac{1}{4\pi R_0^2}\right)\right]^3 \tag{18}$$

Simplifying, multiplying both sides by V-cubed to eliminate Vs in the denominator on the righthand side and rearranging into the standard polynomial form:

$$-\left[\frac{10^{\left(\frac{G}{10}\right)}}{4\pi R_0^2}\right]^3 V^3 + 3\left(\frac{cT_{60}}{\ln 10^6}\right)\left[\frac{10^{\left(\frac{G}{10}\right)}}{4\pi R_0^2}\right]^2 V^2 - \left\{3\left(\frac{cT_{60}}{\ln 10^6}\right)^2\left[\frac{10^{\left(\frac{G}{10}\right)}}{4\pi R_0^2}\right] + \left(\frac{4}{6}\right)^3\right\}V + \left(\frac{cT_{60}}{\ln 10^6}\right)^3 = 0 \tag{19}$$

As a cubic polynomial, it can now be solved according to Cardano's well-known solution to the cubic equation with the coefficients above or solved numerically with a computer. Obviously, there will be three solutions, but only the positive, real-valued solution will represent a real, physical volume useful to the acoustic consultant. Minor adjustments to the equation could be made, such as altering the $S(V)$ function, if appropriate.

5 ANALYSIS OF CONCERT HALL G MEASUREMENTS

It is well-known that Beranek has compiled measured octave-band data of standardized objective acoustical parameters[22]. For many famous rooms, both reverberation time and G are listed, in the unoccupied condition. This data set provides an opportunity to verify if measurements in those real halls follow Rindel's mathematical relationship presented in Figure A.1 in ISO 23591[1], see Table *2*.

Table 2: Theoretical vs. Measured Sound Strength (G) of concert Halls from Beranek[22].

Abbreviation	Concert Hall	Room Volume (CF)	Room Volume (m^3)	Measured G (dB)	Theoretical G (dB)	G Error (dB)
VM	Vienna Musikvereinssaal	530,000	15,000	7.1	7.0	0.1
MET	Metropolitan Opera House	873,000	24,720	0.5	0.8	-0.3
SH	Boston Symphony Hall	662,000	18,750	4.7	4.8	-0.1
AC	Amsterdam Concertgebouw	663,000	18,770	5.8	4.9	0.9
SD	St. David's Hall	777,000	22,000	3.4	2.9	0.5
RA	Royal Albert Hall	3,060,000	86,650	-0.7	-1.7	1.0

The strength error value is measured G_{Mid} minus the theoretical G_{Mid}, per the following equation.

$$G_{err} = G_{meas} - G_{thr} \tag{20}$$

6 MEASURED SOUND STRENGTH (G) RESULTS

The author's sound strength (G) measurements for the rooms listed in Table 1 are shown below. Initial results did not match the curves in ISO 23591 Figure A.1 well, helping to confirm that there were flaws in the measurement setup, as mentioned in section 3. It was determined that the amplifier was overdriven, leading to distortion at the end of the sine-tone sweep. While initially using the internal laptop soundcard with a 3.5 mm jack-to-BNC adapter, the problem was resolved by using an external USB sound card (Sterling Harmony H224 audio interface) with a ¼" TRS-to-BNC cable.

The author's intent is to return to the lab to complete the calibration procedure[18] with the updated signal chain. For logistical reasons, this was not done prior to submission of this paper. As an interim way to review results, a simplified "in-situ calibration" method was employed per Hak et al.[19]

In each room, impulse responses at multiple receiver positions are measured for a given source position, all with a source-receiver distance greater than 3 meters, per ISO 3382-1, Section A.2.1[17]. Hak et al. use equation A.4 of this standard (see Equation 21 below) as part of an "in-situ" calibration in concert halls, which are reverberant. Based on Hak's process, multiple IRs are measured in eight angular increments of 45°, and an averaged impulse response is then used to calculate the sound exposure level $L_{pE,10}$ at 10 m. Time constraints mean fewer IR measurements than Hak's procedure were taken. Therefore, the following measurements presented are expected to have lower precision than Hak's in-situ methodology[19]. In some instances only one measurement is being used to calculate the 10 m level with the understanding that this does not fully account for the directivity of the source; in other instances, 90° increments (four positions) are used. The uncalibrated "Direct SPL" octave band values $L_{pE,d}$ from Odeon measured at some source-receiver distance d are here used to calculate $L_{pE,10}$ in octave bands using Equation 21:

$$L_{pE,10} = L_{pE,d} + 20\log(d/10) \quad (21)$$

Subtracting the octave band sound pressure exposure level at 10 meters (Equation 21) from the measured uncalibrated "SPL" octave band values from Odeon for each measurement position yield the work-around octave band G values for the simplified "in-situ calibration" based on Hak et al.[19]

This value $L_{pE,10}$ is then subtracted from each other measurement position's L_{pE}, taken based on the uncalibrated "SPL" row of data output from Odeon software. In a case where 4 measurement positions greater than 3 meters are taken, it is assumed that a direct SPL measurement cannot be used to calibrate its own overall SPL measurement; therefore, measurement position 1 is used as the "direct" value to calibrate "overall" values for positions 2-4, going through all 4 permutations in turn, and averaging the G values thus obtained. In this way, the intent of angular increments from Hak[19] is maintained, while minimizing the number of measurement positions required in a small room.

Employing one of these simplified versions of the "in situ calibration" described by Hak et al.[19], the 500 Hz and 1000 Hz octave band values for G are averaged to result in a single-value G_{Meas}. This G_{Meas} is compared to the theoretical G_{Thr} value from Equation 15 to obtain G_{err} (Equation 20). The spatial average of the $T30$s generated by Odeon are used. In Table 3, the numeric sound strength results, including the sound strength error, are presented. Figure 2 plots the G_{err} against room volume, with mean and standard deviation (+/-) of the measured data also plotted as dashed lines.

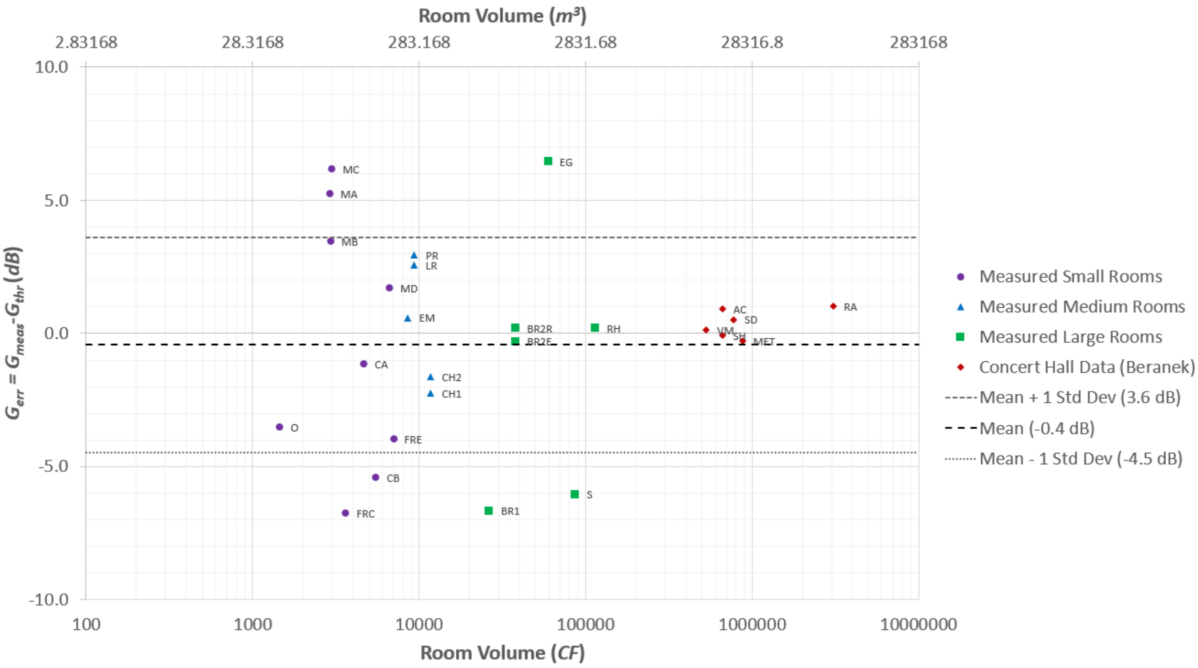

Figure 2: Sound Strength Error G_{err} as a function of room volume in cubic feet (or m^3). Rooms of small, medium, large, and concert hall volumes categorized by room type/size. The mean and standard deviation ($\pm 4.0\ dB$) exclude the Beranek data.

Table 3: Theoretical G, Measured G, and G error results by room.

Abbreviation	Room Description	Volume (CF)	Volume (m^3)	G_{thr}	G_{meas}	G_{err}
O	Office	1,455	41	23.8	20.3	-3.5
MA	Meeting Room A	2,899	82	21.7	26.9	5.2
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S	Sanctuary	87,025	2,464	13.0	6.9	-6.1
RH	Recital Hall	114,320	3,237	7.2	7.3	0.2

7 DISCUSSION

The mean sound strength error G_{err} of the $N = 20$ data points (17 rooms) is -0.4 dB, and the standard population deviation is ±4.0 dB. The obvious observation that is suggested by Figure 2 is that the sound strength error appears to be greater for rooms of smaller volume, and less for rooms of greater volume, particularly if the Beranek data (see Table *2*) is included. This matches expectations; recall that Rindel's derivation[3] depends on the assumption that the room is diffuse[13] which, small rooms generally are not.

For all presented measurements, it is important to acknowledge that, since the simplified "in situ calibration" method is used, it is expected that the results will have more uncertainty than Hak et al.[19] because (1) the full angular measurement regime used by Hak for in-situ calibration was not achieved in this data set, and (2) overall fewer measurements beyond the "angular" measurements were taken in concession to time constraints for field measurements.

That said, perhaps the most useful comparison that can be made at this juncture *is* to Hak's error analysis. Are the sound strength errors against Rindel's theory more or less than the uncertainty in Hak's corresponding G measurement uncertainty in a concert hall setting? The deviation of Hak from the average of precision methods for the in-situ calibration method was -0.2 dB for his Stage A condition, and 0.3 dB for his Stage B condition[19]. Obviously, ±4.0 dB is substantially larger than these values. If the reason for the sound strength error is due to the measurement as opposed to the theoretical calculation not being a good model, then it seems reasonable that, once full calibration of the signal chain used by the author is achieved, this variation will be minimized.

8 CONCLUSION

The mathematics behind ISO-23591 are presented and expanded upon. It is recommended that the next iteration of this standard includes equations (14) and (15) as well as a discussion of surface area function $S(V)$ assumptions, which will be more practical for acoustical researchers and consultants to use than only being able to reference Figure A.1. A third equation (19) is presented as a way for a consultant to choose the appropriate G and T for a room and determine the room volume needed to achieve those goals, enabling the consultant to have evidence to support their position that the height/room volume must be increased in particular cases to meet design goals despite cost implications.

The measurement rig and calibration process were described, along with the challenges encountered. The simplified "in-situ" process is implemented to see results in the near term, with the long-term goal to complete the calibration process[18] at NWAA Labs with the updated signal chain at a later date.

Measured G is compared to calculated G under the ISO 23591 framework both for the data gathered by the author, and with historical data from Beranek[22]. The present findings suggest that measurements can agree reasonably with the model, particularly in rooms of larger volume. The promising results suggest that many more rooms should be tested and evaluated against the ISO 23591 framework to gain better statistical insight into the accuracy and precision of the mathematical model. Qualitatively, this study clearly shows that while G historically has been a measure associated primarily with concert halls, there is value in measuring and understand G for rooms of many types, particularly where there is a combination of multiple simultaneous sound sources. The author views ISO 23591 analysis as having potential insight for rooms such as: concert halls, band rooms, choir rooms, orchestra rooms, church sanctuaries, atriums, gyms, cafeterias, bars, restaurants, banquet halls, and ballrooms.

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