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Atmospheric Room Acoustic Normalization in the Oslo Opera House

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The room acoustics in the main auditorium Store Sal at the Oslo Opera was measured on three different occasions in 2023. The purpose was to verify that the perceived room acoustics of the hall remained unchanged after modifying the mounting of the balcony ceilings. The original reflective wooden panels were glued and had begun to detach. A new mounting solution for all the balcony ceilings was initiated by Statsbygg for safety reasons. Several room acoustic parameters were measured in octave bands and evaluated according to ISO 3382-1:2009. The measurements were carried out in February, July, and September in 2023. Whilst the temperature was consistently around 20 °C on all three occasions, the relative humidity varied: 31% RH in February, 52% RH in July, and 40% RH in September. This resulted in significantly different reverberation times in the 2000 Hz, 4000 Hz, and 8000 Hz octave bands, as expected. An even greater deviation appeared at the higher frequencies when applying atmospheric normalization for air attenuation using a previous normalization method based on Harris's correction method in one third octave bands. The measurement system was rigorously checked, and the measurements were also repeated with a different system, resulting in the same results. This led to the conclusion that the atmospheric correction method overestimated the air attenuation. By applying a novel method for normalization in octave bands recently developed by Rindel, the measured reverberation times resulted within < 1 JND for the three occasions.

1 Introduction

It is well known that the temperature and relative humidity (RH) influence the reverberation time, especially at high frequencies. The air absorption is higher in dry air than in humid air, as the molar concentration of water vapor acts as a catalyst for the relaxation of oxygen and nitrogen in the air [1]. The RH is dependent on temperature, and if the absolute humidity is constant, increased temperature will lead to decreased RH, which means that the air absorption could be unchanged if the temperature decreases and the RH increases. However, if the temperature is being kept constant, the air absorption will increase as the RH decreases. In other words, the reverberation time will be shorter as the air gets dryer. Musicians also tend to categorise the acoustics as *dry* when the reverberation time is short, which fits well with the case of a hall with dry air. The air absorption, however, is negligible at low frequencies, but increases rapidly with frequencies above 1 kHz.

In Scandinavia, the RH can get very low in the winter season, especially indoors when cold dry air from the outside gets warmed up indoors, the RH reduces drastically. Thus, is not unusual to measure RH as low as 10-20% in the winter season. Perhaps this means that a concert can be perceived as having less *brilliance* in the sound in the winter compared to the summer season, unless the concert hall has a constant climate regulation.

The International Standard ISO 3382-1:2009 [2] states that "The temperature and relative humidity of the air in the room should be measured to an accuracy of ± 1° C and ± 5 %, respectively". The standard does not mention what to do with those measurements, or how to normalize the atmosphere for example when measurements with different air conditions need to be compared.

In 1966, Harris suggested that “In presenting reverberation-time data for large auditoriums, irrespective of the humidity and temperature at which measurements are made, correct the reverberation time so that it represents the reverberation time that would have been obtained if the measurements had been made at a relative humidity of 50% and a temperature of 20 ◦C, i.e., standard conditions” [3]. Harris also suggested a normalization method that uses the air attenuation coefficients for pure tones corresponding to the centre frequency of the one-third octave bands above 2 kHz to 12,5 kHz. Below 2 kHz, the air attenuation coefficients for pure tones that correspond to the centre frequencies of octave bands were applied.

The method is supposed to work well, if the measurements are being performed in one-third octave bands [4]. However, for measurements in octave bands, and for long reverberation times (i.e. long distances for the sound propagation), the method does not yield accurate corrections for high frequencies. This is explained by Rindel [4] a result of the neglection of the non-linear behaviour of the air attenuation in octave bands. Sutherland and Bass [5] describes that the air absorption shapes the spectrum within the octave band as a function of time of propagation, resulting in detecting most of the energy in the lower part of the octave band. Rindel has developed a novel summation method to estimate the octave band energy attenuation coefficient as a function of the time of propagation [4].

It should be mentioned that since the 1960s, it has been common practice to perform reverberation time measurements in concert halls in octave bands [4]. In the second edition of ISO 3382:1997 [6] it was even stated that reverberation time measurements in concert halls should be measured in octave bands. However, ISO 3382-1:2009 does not have this requirement, although it is stated that octave-band measurements give a better measurement accuracy than one-third-octave measurements with the same number of measurement positions [2].

This paper presents measurements of reverberation time in octave bands, of the main auditorium of the Oslo Opera on three different occasions in 2023. Whilst the temperature was consistently around 20 °C on all three occasions, the relative humidity varied: 31% RH in February, 52% RH in July, and 40% RH in September. Furthermore, the measurements were initially normalized to standard atmosphere (20 °C, 50% RH) using a method implemented in Odeon v.17, which was used for the measurements. The method was based on Harris’s correction method for one-third octave bands but applied an average of air absorption coefficients corresponding to the pure tone according to ISO 9613-1 [1] for each one-third octave band centre frequency within each octave band. When realizing the deviations in reverberation time became greater after the normalization, the recently developed method by Rindel, as implemented in Odeon v.18.11, was applied.

Since the temperature and relative humidity on the measurements in July almost represents the standard atmosphere used for normalization of reverberation time, this paper will focus on comparing the measurements between February and July.

2 The Oslo Opera House

In 2023 Statsbygg initiated a process to replace the mounting of the balcony ceilings in the main auditorium, *Store Sal*, of the Oslo Opera House. The original reflective wooden panels were glued and had begun to detach, thus the need of a new, safe mounting. The opera house was completed in 2007, and the horseshoe-shaped main auditorium seats 1364. The main auditorium is considered to have world class acoustics and is frequently used for on stage concerts as well.

3 The measurements

The measurements in the opera’s main auditorium were carried out in 2023 in February, before any changes to the balconies were made, then in July after remounting ceilings of the second balconies, and finally in September, after remounting ceilings of the first balconies as well.

The measurements had to be performed at night to not disturb the everyday activities in the hall. The fire curtain/iron curtain separating the main stage from the audience area was thus lowered, as shown in the right-hand photograph in Figure 1 during all measurements.

For security reasons due to unstable balcony ceiling panels beneath, parts of the balconies were temporarily closed to the public. This was done by using black drapes, which can be seen in the left-hand photograph in Figure 1. The drapes were acoustically transparent and therefore not expected to affect the room acoustics noticeably. This aligns with user feedback on the acoustics of the hall following the installation of the drapes. The measurements taken before the remedial work were carried out with these drapes in place, and for the situation after the remounting was measured without the drapes.

For the measurement in July, the orchestra pit floor was elevated, expanding the stage floor, as shown in the right-hand photograph in Figure 1. The chairs, music stands and instruments in the orchestra pit had been removed, reducing absorption and scattering close to the sound source. The elevated floor creates a stronger floor reflection for the

measurements. This is unfortunately a change in the room conditions, and some minor deviations in the measurements were to be expected. In September, the room conditions were almost the same as for the February measurements, as shown in the left-hand photograph in Figure 1.

Figure 1: The loudspeaker, orchestra pit and the acoustically transparent black drapes on 1st and 2nd balconies (left). Orchestra pit floor elevated creating an extended stage floor (right). Photo: Erik Arvidsson

The loudspeaker was placed in two different positions on the stage. In both cases, it was positioned 0.9 m from the iron curtain and at a height of 1.5 m. The room impulse responses were measured at seated ear height up to 16 measurements for each source position. The measurement positions were arranged over the stage left half of the hall, covering the side of the 1st balcony, 2nd balcony as well as the stalls. Source and microphone positions were the same on all three days of measurements. The sound source used for the measurements was the Odeon Omni, together with the Odeon software v.17 and the swept sine technique. For most of the measurement positions, multiple measurements were performed with different sweep lengths varying from 10-60 seconds to ensure sufficient signal-to-noise ratio especially in the lower frequencies.

The measurement system was rigorously checked, and a test with a more powerful loudspeaker and amplifier was performed as well. This was to ensure consistency of the results and that the measurements with the Odeon Omni yielded sufficient signal-to-noise ratio, as the Odeon Omni was relatively new at the time and this was the first time it was used for such a large volume. This test was also important in order to rule out potential sources of error in the higher frequencies, especially since the normalization of air absorption seemed unexpectedly overestimated on the first day of measurement.

Shortly after the first day of measurements, Rindel was consulted on the normalization of air absorption which was implemented in the Odeon software (v. 17). Rindel, who was aware of this issue, was in the process of developing a summation and approximation method for normalization of air attenuation in octave bands. The summation method was first implemented in Odeon v. 18.11 and is briefly described in the following chapter.

4 The summation method

In a recent article, Rindel [4] suggests a summation method for normalization of impulse responses due to air attenuation. The summation method calculates the octave-band energy attenuation as a function of the time of propagation. The summation method requires a correction of each time sample in the measured impulse response, which is quite heavy computationally. An alternative to the summation method is to apply Fourier transforms of time samples of the impulse response, and inverse Fourier transforms back to the time domain after the correction for air attenuation.

The decay curve is the relative sound pressure level as a function of time, and the time is relative to the arrival of the direct sound at the receiver. The distances of the total sound paths are measured from the sound source, and the arrival time of each reflection can be converted to the total distance of the reflection paths. Since the speed of sound changes

with the temperature of air, this will affect the time scale of the impulse responses. To compensate for the temperature effect on the speed of sound, the decay curve is converted to the distance domain before applying the air absorption corrections.

The air energy attenuation coefficients are then applied according to ISO 9613-1 [1] for a number of frequencies within the octave-band. The energy attenuation of the octave-band average varies as a function of traveling distance for the sound wave. Since the air attenuation increases with frequency within the octave band, the octave band is divided into N=9 frequencies, and the attenuation coefficient for each frequency within the octave band is applied.

Then the last step is to convert the corrected squared impulse responses for each octave band back to the time domain.

In this normalization method, the distance from the source to the receiver should in principle be known. Rindel however suggests that a distance of 10 meters is to be used if the actual distance is unknown.

This summation method is implemented in the Odeon software, for v. 18.11 and later versions.

5 Results

The measured room acoustic parameters EDT_{m} (*perceived reverberance), $D_{50\mathrm{m}}$, $C_{80\mathrm{m}}$ (perceived clarity of sound),* and G_m *(subjective level of sound)* deviated less than 1 *JND* for all measurements on the three occasions in February, July and September (where $_{\mathrm{m}}$ is the average of 500 and 1000 Hz according to ISO 3382-1:2009).

Figure 2 shows the measured reverberation time, T_{20}, for February (31% RH) and for July (52% RH) together with the normalization of the averaged one-third octave band centre frequencies correction for each octave band (*Previous method*) and the normalization of the summation method (*Rindel*). The figure shows an average of all measurements on the 2nd balcony for two loudspeaker positions on the stage. From 1000 Hz and above, it is evident that the air absorption is contributing to a significant difference between the measurements in February and July. It is also very clear that, from 1000 Hz and above, normalization with the previous method produces an even greater deviation in the reverberation time.

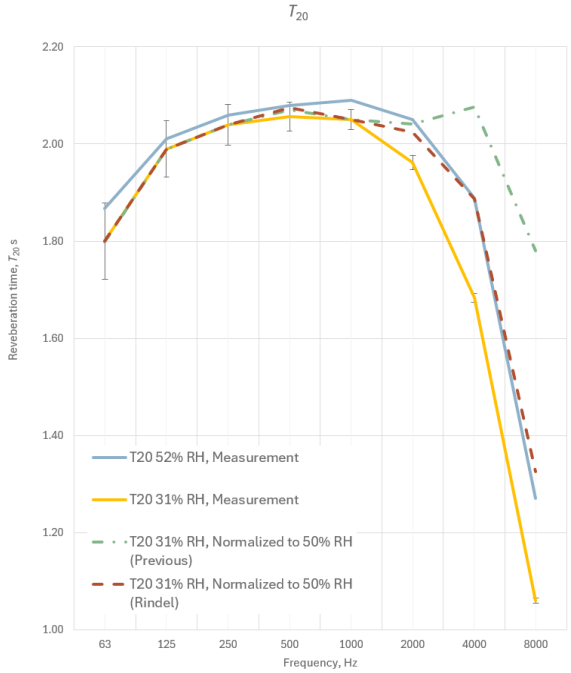

Figure 2: Measured Reverberation time T_{20} for February (RH 31%) with; no correction; Previous normalization method and Rindel's summation method, and for July (RH 52%) with no correction.

In the following figures, only the octave bands 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz are presented since those are the frequencies of interest regarding the air attenuation.

Figure *3* shows the measured Early Decay Time, *EDT*, for the same receiver and source position, *H1M1*, for February (RH 31%) with; *no correction*; Previous normalization method and Rindel's summation method, and for July (RH 52%) with no correction.

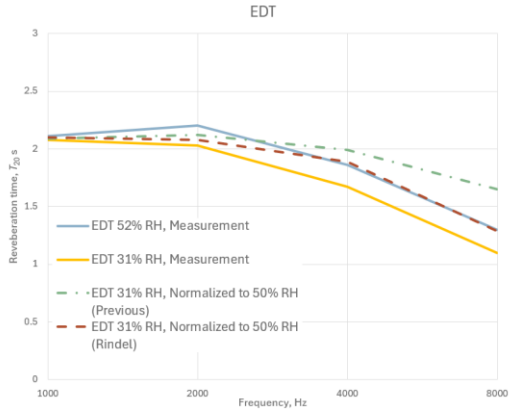

Figure 3: Measured Early decay time (EDT) for H1M1, February (RH 31%) with; no correction; Previous normalization method and Rindel's summation method, and for July (RH 52%) with no correction.

Figure *4* and Figure *5* shows the measured T_{20} and T_{30} respectively, for the same receiver position and source position, *H1M1*, for February (RH 31%) with; *no correction*; Previous normalization method and Rindel's summation method, and for July (RH 52%) with no correction.

Figure 4: Measured Reverberation time T_{20} for H1M1, February (RH 31%) with; no correction; Previous normalization method and Rindel's summation method, and for July (RH 52%) with no correction.

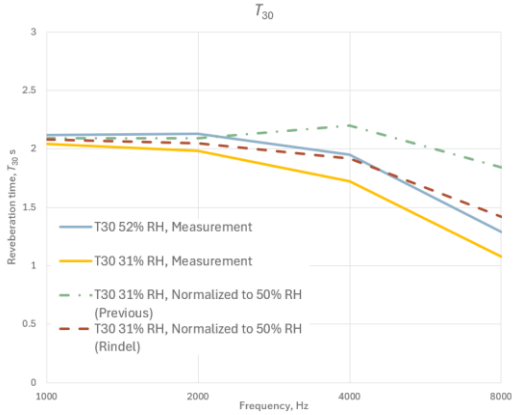

Figure 5: Measured Reverberation time T_{30} for H1M1, February (RH 31%) with; no correction; Previous normalization method and Rindel's normalization method, and for July (RH 52%) with no correction.

The relative deviation between the measurements in microphone position *H1M1* for February (RH 31%) and July (RH 52%) is presented in Table 1, for the octave bands 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz. The deviation is presented in seconds and percent. The Just Noticeable Difference, *JND,* is also presented where 1 *JND* corresponds to a 5 % change in perceived reverberance, *EDT,* according to ISO 3382-1:2009.

Table 1: Relative deviation in measured early decay time, *EDT*, reverberation time T_{20}, and T_{30} for February with; no correction; Previous normalization and Rindel's normalization applied, compared to measurements in July with no correction, for measurement position *H1M1*.

	Description	RH [%]	Frequency, Hz			
			1000	2000	4000	8000
Δ *EDT* [s]	Measurement	31	0.0	-0.2	-0.2	-0.2
Δ *EDT* [%]	Measurement	31	-1	-8	-10	-15
Δ T_{20} [s]	Measurement	31	-0.1	-0.1	-0.3	-0.2
Δ T_{20} [%]	Measurement	31	-4	-5	-14	-15
Δ T_{30} [s]	Measurement	31	-0.1	-0.2	-0.2	-0.2
Δ T_{30} [%]	Measurement	31	-4	-7	-12	-16
JND	Measurement	31	< 1	1.5	2	3
Δ *EDT* [s]	Norm. Previous	50	0.0	-0.1	0.1	0.4
Δ *EDT* [%]	Norm. Previous	50	-1	-4	7	27
Δ T_{20} [s]	Norm. Previous	50	-0.1	0.0	0.1	0.6
Δ T_{20} [%]	Norm. Previous	50	-4	0	7	45
Δ T_{30} [s]	Norm. Previous	50	0.0	0.0	0.3	0.6
Δ T_{30} [%]	Norm. Previous	50	-1	-2	13	43
JND	Norm. Previous	50	< 1	< 1	2	5
Δ *EDT* [s]	Norm. Rindel	50	0.0	-0.1	0.0	0.0
Δ *EDT* [%]	Norm. Rindel	50	0	-5	2	-1
Δ T_{20} [s]	Norm. Rindel	50	-0.1	0.0	0.0	0.1
Δ T_{20} [%]	Norm. Rindel	50	-4	0	-2	5
Δ T_{30} [s]	Norm. Rindel	50	0.0	-0.1	0.0	0.1
Δ T_{30} [%]	Norm. Rindel	50	-2	-4	-2	10
JND	Norm. Rindel	50	< 1	1	< 1	< 1

The relative deviation between the measurements averaged for all 2nd balcony receivers for February (RH 31%) and July (RH 52%) is presented in Table 2, for the octave bands 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz. The deviation is presented in seconds and percent. The Just Noticeable Difference, *JND,* is also presented where 1 *JND* corresponds to a 5 % change in perceived reverberance, *EDT,* according to ISO 3382-1:2009.

Table 2: Relative deviation in measured early decay time, *EDT*, reverberation time T_{20}, and T_{30} for February with; no correction; Previous normalization and Rindel's normalization applied, compared to measurements in July with no correction, average for all 2nd balcony measurements.

	Description	RH [%]	Frequency, Hz			
			1000	2000	4000	8000
Δ *EDT* [s]	Measurement	31	-0.1	-0.1	-0.2	-0.3
Δ *EDT* [%]	Measurement	31	-3	-5	-9	-21
Δ T_{20} [s]	Measurement	31	-0.1	-0.1	-0.2	-0.2
Δ T_{20} [%]	Measurement	31	-3	-7	-11	-13
Δ T_{30} [s]	Measurement	31	-0.1	-0.2	-0.2	-0.2
Δ T_{30} [%]	Measurement	31	-5	-7	-10	-14
JND	Measurement	31	< 1	1	1.8	4
Δ *EDT* [s]	Norm. Previous	50	-0.1	0.0	0.1	0.2
Δ *EDT* [%]	Norm. Previous	50	-3	-1	7	15
Δ T_{20} [s]	Norm. Previous	50	-0.1	-0.1	0.2	0.6
Δ T_{20} [%]	Norm. Previous	50	-5	-3	10	46
Δ T_{30} [s]	Norm. Previous	50	-0.1	-0.1	0.2	0.7
Δ T_{30} [%]	Norm. Previous	50	-4	-3	13	52
JND	Norm. Previous	50	< 1	< 1	1.5	3
Δ *EDT* [s]	Norm. Rindel	50	-0.1	0.0	0.0	0.0
Δ *EDT* [%]	Norm. Rindel	50	-4	0	1	1
Δ T_{20} [s]	Norm. Rindel	50	-0.1	-0.1	0.0	0.1
Δ T_{20} [%]	Norm. Rindel	50	-5	-4	0	8
Δ T_{30} [s]	Norm. Rindel	50	-0.1	-0.1	0.0	0.1
Δ T_{30} [%]	Norm. Rindel	50	-4	-4	0	10
JND	Norm. Rindel	50	< 1	< 1	< 1	< 1

Table 3 shows the measurement uncertainty for the averaged 2nd balcony measurements, as the standard deviation for T_{20} and T_{30} respectively according to ISO 3382-1:2009.

Table 3: Measurement uncertainty calculated as the standard deviation according to ISO 3382-1:2009 for T_{20} and T_{30} for the measurements in February (31 %) and July (52 %).

		Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
σ T_{20}	31 %	0.08	0.06	0.04	0.03	0.02	0.01	0.01	0.01
σ T_{30}	31 %	0.05	0.04	0.03	0.02	0.01	0.01	0.01	0.00
σ T_{20}	52 %	0.08	0.06	0.04	0.03	0.02	0.02	0.01	0.01
σ T_{30}	52 %	0.05	0.04	0.03	0.02	0.01	0.01	0.01	0.00

6 Discussion

The normalization according to the summation method suggested by Rindel, shows good correlation with the measured reverberation time in July. It should be noted that the relative humidity for the normalization is 50%, and the actual relative humidity in July was measured to 52%. It is assumed that the 2% difference is negligible. It should also be noted that the method assumes a homogeneous temperature and relative humidity throughout the whole volume, which is not fully realistic.

In general, the reverberation time was slightly longer in July than in February for all frequencies. This is probably due to the change in the conditions of the room, since the orchestra pit was elevated to an extended stage. The measured values of clarity, C_{80} for lower to mid frequencies, also support this as there is more early energy relative to late energy, as one should expect with support from the floor reflections close to the sound source. However, the clarity C_{80} is generally higher in February than in July, for frequencies above 1000 Hz.

It is interesting to think of the perceived *brilliance* as more prominent in the summer when the air absorption is reduced due to more relative humidity in the air, leading to a longer reverberation time in the higher frequencies. On the contrary, in the winter, when the relative humidity is low, the air attenuation is higher as a function of the time of propagation, leading to more early than late energy, the *clarity* will thus increase compared to the summer.

A central question is whether the changes in the higher frequencies are noticeable. ISO 3382-1:2009 only states *JND* limits for the mid-frequencies, i.e. average of 500 Hz and 1000 Hz, for the following room acoustic parameters; *G*, *EDT,* C_{80}, $D_{50,}$ T_s, J_{LF} *and* $J_{LFC.}$ In this case, the task was to assess whether the perceived room acoustics was changed for the balconies, and the chosen room acoustic parameters to analyse were the *subjective level of sound*, *G*, the *perceived reverberance*, *EDT* and the *perceived clarity of sound*, C_{80} *and* $D_{50.}$

Even though the mid-frequency averages are less than 1 *JND* for all investigated parameters, it remains a problem to determine the possible perceived changes especially in higher frequencies. For example, the *EDT* deviates on average 21% for 8000 Hz between February and July. It is reasonable to assume that this would represent a significant and noticeable change in perceived reverberance. Another question is whether the *JND* limits for *EDT* also apply to changes in reverberation time, specifically T_{20m} and $T_{30m.}$

References

[1] ISO 9613-1; Acoustics – Attenuation of Sound During Propagation Outdoors – Part 1: Calculation of the Absorption of Sound by the Atmosphere, *International Organization for Standardization,* Geneva, 1993.

[2] ISO 3382-1; Acoustics – Measurement of Room Acoustic Parameters – Part 1: Performance Spaces. *International Organization for Standardization*, Geneva, 2009.

[3] C. M. Harris, Absorption of Sound in Air versus Humidity and Temperature*, J. Acoust. Soc. Am.* 1966, 40, 148-159.

[4] J. H. Rindel, Air attenuation in octave bands and how to normalize room acoustic measurements to a standard atmosphere, *Applied Sciences,* 2024, 14, 22, 10139. DOI: 10.3390/app142210139.

[5] L. C. Sutherland and H. E. Bass, Influence of atmospheric absorption on the propagation of bands of noise, *J. Acoust. Soc. Am.* 1979, 66, 885-894.

[6] ISO 3382; Acoustics – Measurement of Reverberation Time in Auditoria with Reference to Other Acoustical Parameters, International 2nd edition*, Organization for Standardization,* Geneva, 1997.