Morten Andreas Edvardsen

Analysis of measurements from Norwegian venues for amplified music

Master's thesis in Civil and Environmental Engineering
Supervisor: Anders Homb
Co-supervisor: Jan Olav Owren, Peter Svensson, Bård Støfringsdal
June 2021

Master's thesis

NTNU
Norwegian University of Science and Technology
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COWI

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Abstract

This study has two main objectives. Firstly, to quantify the uncertainty of room impulse responses calculated from FFT-based deconvolution of recordings in one receiver position of exponential sine sweeps (ESS) played through a PA system. Secondly, to analyse a database containing measurements of more than 4300 concerts from Norwegian concert venues. The purpose is to gain knowledge on sound levels at concerts in Norwegian venues and increase the focus on sound levels at amplified concerts.

In recent years, the focus on sound levels at amplified concerts has increased both in the industry and among external parties, and in 2017 Kulturrom initiated a project where they subsidised more than one hundred Norwegian concert venues with equipment to measure sound levels at concerts. In addition to measurements of concerts, participating venues have recorded an ESS played through the PA system to gain information about the reverberation time of each venue. However, apart from a study by Støfringsdal in 2018, little research has been done on this database. To address this, the author has measured reverberation time in six participating venues using ISO 3382-1 and analysed a subset of the database containing 621 concerts.

Results indicate that reverberation time can be measured in one position using ESS played via a PA system with reasonable accuracy in octave bands down to 250 Hz. A substantial amount of concerts has a max $L_{A,Eq,15\text{ min}}$ level close to the warning level of 102 dB, and 14 % of the concerts exceeded the warning level. Significant correlation were found between the mean max $L_{A,Eq,15\text{ min}}$ level of each venue and room volume, room height, D_{50}, and bass ratio. Moreover, significant correlations were found between room volume and $T_{20,W}$ (63-2000 Hz). However, these acoustic properties are derived from the recordings of ESS and will therefore have high uncertainty.

In conclusion, recordings of ESS played via a PA system can be used for quick analysis of reverberation time at concert venues where accuracy at low frequency is not crucial. The analysis of Kulturrom's database shows that more work is needed to increase the focus on sound levels in the industry. Furthermore, when designing venues for amplified music, the acoustic design criteria may affect the sound level of concerts.

Sammendrag

Denne studien har to mål. For det første, å kvantifisere usikkerheten av romimpulsresponser beregnet med FFT-basert dekonvolusjon av opptak i en mottakerposisjon av eksponentielle sinussveip (ESS) spilt av med et PA-system. For det andre, å analysere en database med målinger av mer enn 4300 konserter fra norske konsertscener. Hensikten er å øke kunnskapen om lydeksponering på norske konsertsteder, samt øke fokus på lydnivå ved konserter for forsterket musikk.

I nyere tid har fokuset på lydnivå ved konserter for forsterket musikk økt både i industrien og blant eksterne parter. I 2017 satte Kulturrom i gang et prosjekt der de subsidierte mer enn 100 norske konsertscener for forsterket musikk med utstyr for å måle lydnivå på konserter. I tillegg til lydnivåmålinger ved konserter, har deltakende konsertscener tatt opp et ESS avspilt med PA-systemet for å oppnå informasjon om etterklangstiden. Bortsett fra en studie av Støfringsdal i 2018, har lite forskning blitt gjort på databasen. For å løse dette, har forfatteren målt etterklangstid ved seks deltakende konsertscener med bruk av ISO 3382-1, og analysert en delmengde av databasen på 621 konserter.

Resultatene indikerer at etterklangstiden kan bli målt i en posisjon med bruk av ESS spilt av med et PA-system med rimelig nøyaktighet i oktavbånd ned til 250 Hz. En betydelig andel av konsertene har et maks $L_{A,Eq,15\ \mathrm{min}}$-nivå nært varslingsgrensen på 102 dB, og 14 % av konsertene oversteg varslingsgrensen. Signifikant korrelasjon ble funnet mellom det gjennomsnittlige maks $L_{A,Eq,15\ \mathrm{min}}$-nivået ved hver scene og romvolum, romhøyde, D_{50} og bass ratio. Dessuten ble signifikant korrelasjon funnet mellom romvolum og $T_{20,W}$ (63-2000 Hz). Disse akustiske parameterne er utledet fra opptakene av ESS, og vil derfor ha høy usikkerhet.

Til slutt, FFT-basert dekonvolusjon av opptak av ESS i en mottakerposisjon avspilt med et PA-system kan brukes til enkel analyse av etterklangstid når usikkerheten ved lave frekvenser ikke er avgjørende. Analysen av Kulturroms database viser at mer arbeid må gjøres for å øke fokuset på lydnivåer i industrien. I tillegg kan valg av akustiske designkriterier i prosjekteringsfasen påvirke lydnivået på konserter.

Preface

This study marks the end of my master's degree at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology.

Music and sound have been a big part of who I am and everything I like throughout my life. Therefore, it always felt natural for me to choose acoustics as a study path. This master thesis has allowed me to combine the research of two interests: live music and acoustic theory.

The topic of this study was suggested by Bård Støfringsdal and Jan Olav Owren from COWI as a continuation of previous work by Støfringsdal. I want to thank both of them for their contributions. Especially, the many meetings and long talks with Owren have been both educational and inspirational.

Professor Peter Svensson has also contributed greatly to this work by giving useful insights on relevant theory, MATLAB code and general advice on the topic. In addition, Svensson has been an inspiration for me personally in the last two years. Seldom have I had a professor that teaches students with such passion, knowledge, and interesting lectures.

When measuring reverberation time in this study, my friend and fellow acoustic student Haavard Vedelden Nøst kindly offered his help, which was greatly appreciated.

During the course of this work, I have also worked part-time as an acoustic consultant at Rambøll in Trondheim. I want to thank my colleagues for the many inspirational conversations throughout this past semester and for lending me measurement equipment and software licenses.

Lastly, I would like to thank my friends at the university who have significantly impacted my life in the past years and contributed to what has become five fantastic years at NTNU.

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Chapter 1

Introduction

In recent years, the focus on hearing damage and sound levels at amplified concerts has increased among audience members and the industry. Norway's largest subsidy scheme for music equipment, Kulturrom (f.k.a. Musikkutstyrsordningen), initiated a project in 2017 to subsidise Norwegian concert venues for amplified music with equipment for sound level logging, where all measurement logs are uploaded to a common database. Kulturrom's project intends to reduce the sound level of concerts and increase the sound engineers focus on the relation between subjective and objective sound levels.

In 2015, the World Health Organization (WHO) put together a group of researchers and industry experts to form a campaign called *Make Listening Safe*. The group estimates that 1.1 billion young people worldwide could be at risk of hearing loss due to unsafe listening practices where recreational listening such as amplified concerts is one of the concerns [1]. Loud concerts put both regular attendees and workers at concert venues at risk of developing tinnitus and hearing loss. Studies have shown that the consequences of such conditions can affect an individual's ability to communicate, leading to social isolation and difficulties in education and employment [2].

Støfringsdal [3] performed a study in 2018 on Kulturrom's database, which contains information from concerts at all included venues. When the study by Støfringsdal was published, the full data set consisted of approximately 300 concerts and events, and he studied a subset of 170 concerts. As of 2021, the data set consists of more than 4300 concerts and events, so many things are still to learn from the data set. Moreover, since 2018, participating venues have received an audio file with an exponential sine sweep (ESS) which was to be played back through the loudspeaker system and recorded with the sound level logging system provided by Kulturrom. Using the recording of the ESS, one can obtain the room's impulse response and find acoustic parameters such as reverberation time.

This thesis has two main objectives. Firstly, quantify the uncertainty of the reverberation time found by FFT-based deconvolution of recordings of ESS in one receiver position played through a PA system. Secondly, we will explore Kulturrom's database of measured concerts by looking at general sound level data and search for statistical correlation between the mean max $L_{A,Eq,15\text{ min}}$ level of each venue and parameters such as reverberation time, bass ratio, hall geometry, early decay time, and definition.

Chapter 2

Background

In Støfringsdal's study from 2018 [3], the background of the project by Kulturrom is thoroughly explained. In this chapter, the author will give some insight into the background and reasoning behind this initiative by Kulturrom.

The issue of high sound levels at Norwegian concerts and events have been picked up extensively in recent years both in the industry and among external parties [4, 5, 6, 7]. There are two main concerns: permanent damage to listeners hearing and noise from the concerts to neighbours. Since its origin in 2009, Kulturrom has been an active voice in the ongoing work to increase the focus on sound levels at Norwegian pop and rock concerts [3], and they aim to reduce the sound levels on amplified concerts in Norwegian venues. One way of increasing the focus and knowledge of the topic is by using sound level meters. Therefore, by March 2021, Kulturrom has rolled out equipment for sound level logging at more than 100 venues.

According to Støfringsdal [3], the project has the following key targets:

- To survey sound levels at permanent venues for amplified music
- To reduce the sound levels on a long-term basis. The industry needs to able to document that such a reduction is happening
- Make concert promoters and the technical manager of the venue more conscious about controlling the sound levels

Kulturrom funds the initiative, and each participant has received the equipment listed in Table 2.1. All participants are obligated to log every concert with popular genres such as pop, rock, jazz, electronic music, world music, and contemporary folk music [8].

Table 2.1: Equipment provided by Kulturrom to all participants

Equipment	**Model**
Computer	Fujitsu w/ Windows 10
Software	WaveCapture RT-Capture 3
Sound card	Focusrite Scarlett 2i2
Microphone	MicW M215L
Calibrator	BSWA CA111
Misc.	touch screen, cables, rack drawer

In general, participating venues have placed the measurement microphone near the mixing position at ear height, usually towards the centre rear part of the room (front-of-house). Such receiver position means that the sound level will generally be lower at the measurement position compared to the audience area closer to the stage.

Kulturrom does not have the authority to decide or impose sound level limits. However, Kulturrom has provided the venue owners with two different warning levels to choose from [8]:

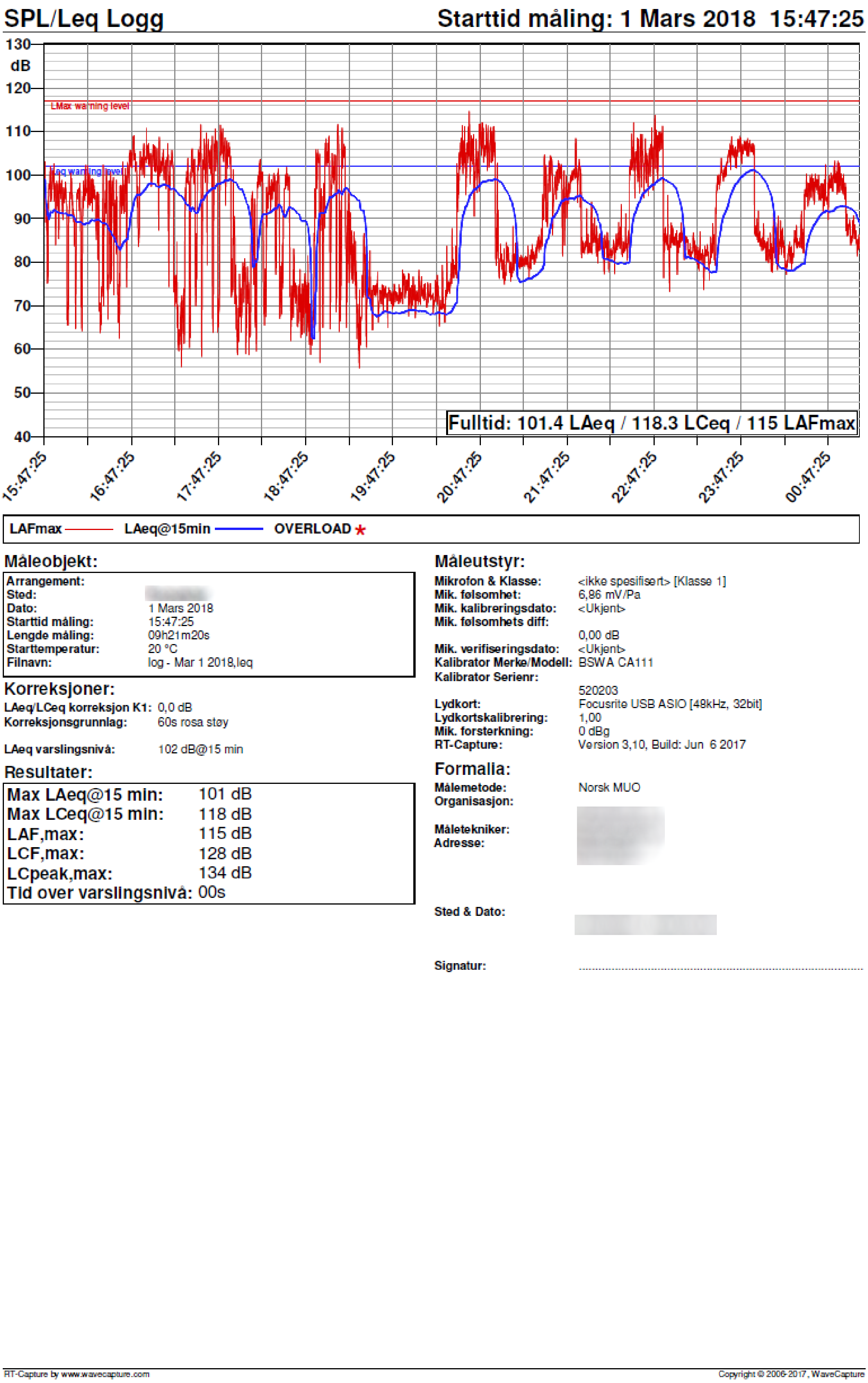
1. $L_{A,Eq,15min} \leq 102$ dB, which corresponds to the Norwegian Directorate of Health's indicative limit value [9].
2. $L_{A,Eq,30min} \leq 99$ dB, which corresponds to the limit value used at Roskilde Festival for several years [3].

Each measurement log is uploaded to a common FTP server. The measurement will, dependent on how much info the sound engineer/measurement technician wants to provide, give the following information in .txt-files:

- information about the artist and venue including an optional comment by the sound engineer;
- start time and length of measurement, as well as date and temperature;
- information about microphone, calibrator, sound card and the calibration sensitivity;
- adopted sound level limit;
- single value levels: Max $L_{A,Eq,15/30min}$, Max $L_{C,Eq,15/30min}$, $L_{AF,max}$, $L_{CF,max}$, $L_{Cpeak,max}$ and time above warning level given in seconds;
- broadband values: $L_{A,Eq,15/30min}$, $L_{C,Eq,15/30min}$, $L_{A,Eq,10s}$, $L_{C,Eq,10s}$, $L_{AF,max}$, $L_{CF,max}$ and $L_{C,Peak}$;
- one-third-octave values: L_{Eq}.

In addition, a .ogg-file containing a lossless audio recording of the entire measurement is uploaded to the server. The purpose is to identify the artist and genre if the sound engineer has not provided such information in the measurement log.

Moreover, the software generates a .pdf file for each measurement, including a summary of key information in the measurement. An example of such a .pdf is given in Figure 2.1.



SPL/Leq Logg **Starttid måling: 1 Mars 2018 15:47:25**

Fulltid: 101.4 LAeq / 118.3 LCeq / 115 LAFmax

LAFmax —— LAeq@15min —— OVERLOAD ★

Måleobjekt:

Arrangement:
Sted: [redacted]
Dato: 1 Mars 2018
Starttid måling: 15:47:25
Lengde måling: 09h21m20s
Starttemperatur: 20 °C
Filnavn: log - Mar 1 2018,leq

Korreksjoner:

LAeq/LCeq korreksjon K1: 0,0 dB
Korreksjonsgrunnlag: 60s rosa støy

LAeq varslingsnivå: 102 dB@15 min

Resultater:

Max LAeq@15 min: 101 dB
Max LCeq@15 min: 118 dB
LAF,max: 115 dB
LCF,max: 128 dB
LCpeak,max: 134 dB
Tid over varslingsnivå: 00s

Måleutstyr:

Mikrofon & Klasse: <ikke spesifisert> [Klasse 1]
Mik. følsomhet: 6,86 mV/Pa
Mik. kalibreringsdato: <Ukjent>
Mik. følsomhets diff: 0,00 dB
Mik. verifiseringsdato: <Ukjent>
Kalibrator Merke/Modell: BSWA CA111
Kalibrator Serienr: 520203
Lydkort: Focusrite USB ASIO [48kHz, 32bit]
Lydkortskalibrering: 1,00
Mik. forsterkning: 0 dBg
RT-Capture: Version 3,10, Build: Jun 6 2017

Formalia:

Målemetode: Norsk MUO
Organisasjon:
Måletekniker:
Adresse:
[redacted]

Sted & Dato: [redacted]

Signatur: ....

RT-Capture by www.wavecapture.com

Figure 2.1: An example of a pdf generated from a measurement log. Sensitive info is blurred to maintain the venues privacy.

Chapter 3

Method

This study's methodology can be split into two parts: one part about measuring reverberation time and one part about the database analysis. In this chapter, we will look at the measurement procedure first.

3.1 Measuring reverberation time

A primary objective in this study is to compare the reverberation times gained by FFT-based deconvolution of recordings in one receiver position of ESS played with professional sound systems against reverberation times achieved by using ISO 3382-1.

3.1.1 Analysis of exponential sine sweep measurements

As mentioned, in 2018, a survey aimed at the participating venues was initiated by Støfringsdal [3]. The survey aimed to gain key data such as venue capacity, stage and audience area and dimensions, sound system setup and whether the venue had been acoustically treated with help from an acoustic consultant.

In addition, an exponential sine sweep (ESS) was distributed with the survey. The technical managers of each venue received the following instructions: download the audio file and play it from a PC connected to the audio system, preferably using an external audio card. If the audio system contains delay speakers, they should be turned off. However, the main sound system, including subwoofers, shall be turned on with the standard setup for concerts. The maximum level while running the test signal should be approximate $L_{A,Eq}$ 95 dB.

The distributed audio file contains an ESS on the left channel, then on the right and finally both channels simultaneously, as shown in Figure 3.1. Hence, it is possible to obtain three impulse responses from the recording. However, in this study, the final recording using both channels simultaneously has not been used as it might increase the uncertainty of the results. As a result, we can find the reverberation time from each recording using one receiver position and two sender positions.

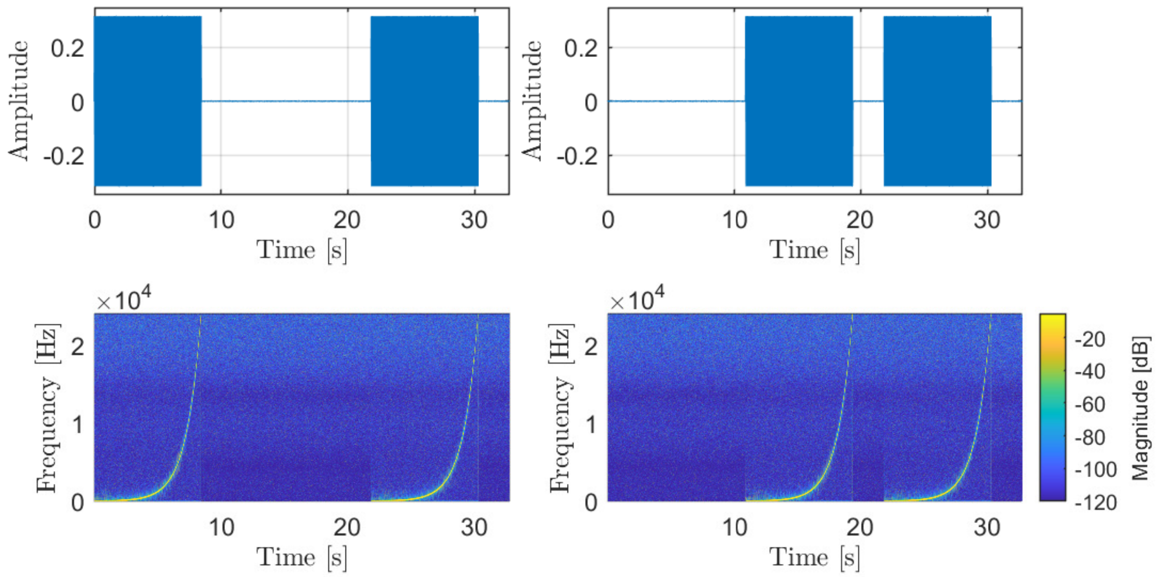


Figure 3.1: A plot of the distributed audio file with the ESS in the time and frequency domain.

The recordings performed by the technical managers of each venue were post-processed in MATLAB to generate impulse responses before analysing them in ODEON and EASERA. The post-processing of these recordings is based on the theory found in Section 4.1, and the MATLAB code can be found in Appendix D. In Figure 3.2, one can see a typical example of such a recording.

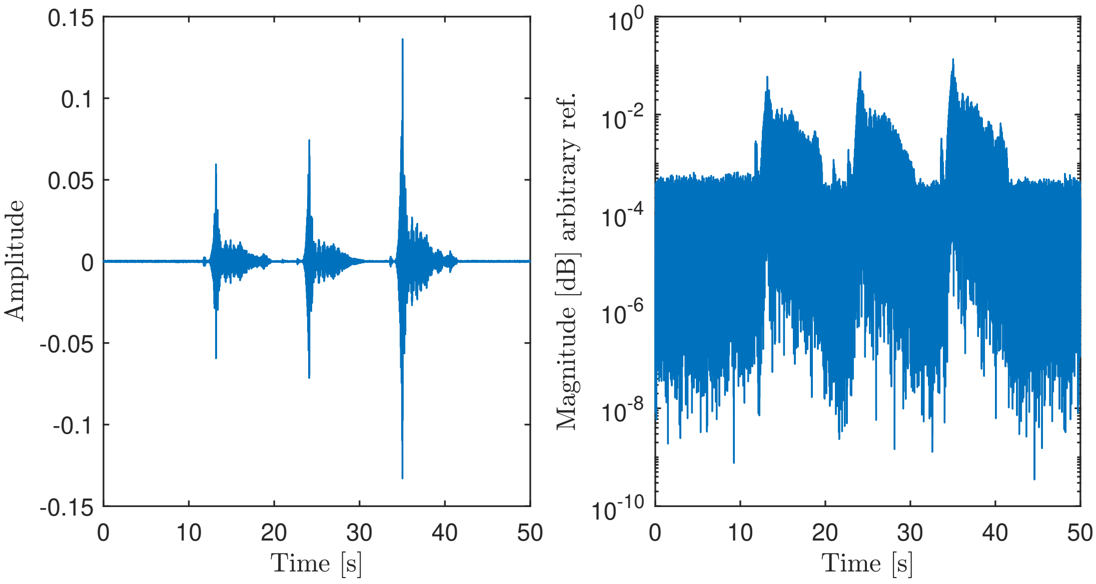


Figure 3.2: Typical example of a recording of the ESS.

As the raw recordings of ESS from different venues neither have the same length nor the same starting time, it was necessary to inspect each recording manually to find a *useful* time-window. When using this manual process, some issues arose. The ESS has a frequency range from 20 Hz to 24 kHz, which is more than expected for most sound systems. Hence, it is not easy to precisely define the beginning and end of each recorded sweep. If the chosen time-window is too late, MATLAB will split the impulse response, i.e., the start of the impulse response will appear at the end. Figure 3.3 illustrates this effect where the upper plot has an appropriate time-window while the lower plot's time-window starts too late. Such effects might give unreliable results in the analysis of the impulse response. Therefore, the author took careful considerations to find an appropriate time-window.

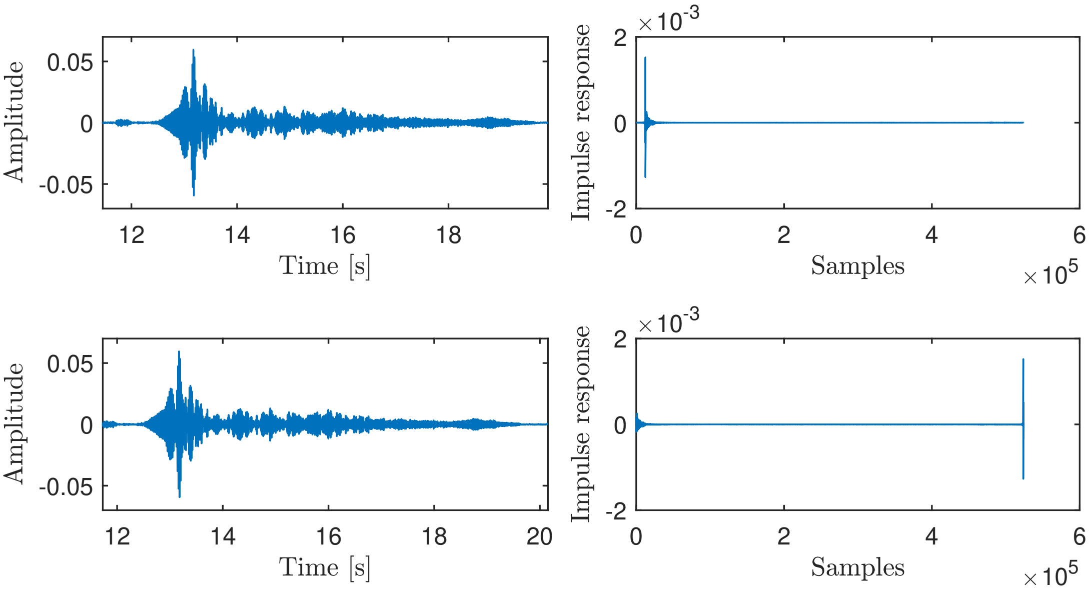


Figure 3.3: An illustration of the importance of choosing an appropriate time-window for the recorded ESS. To the left we see the chosen time-window and to the right we see its associated impulse response.

However, there were also some positive effects of using this manual method. Because it was necessary to inspect all recordings manually, the author discovered some bad recordings. In some cases, the recording was started after the audio file was played, giving useless results.

After generating impulse responses in MATLAB, they were analysed in ODEON and EASERA to find reverberation time in octave bands. During the analysis, the author noticed that the two software gave different results at low frequencies. Consequently, a decision was made to include results from both software.

Unfortunately, there is uncertainty associated with the results gained in this measurement method. Firstly, the measurement procedure does not follow any standard, and the sound system does not meet the requirements set in measurement standards. Secondly, the reverberation time is only measured at one position in the room from two sources, i.e., the left and right side of the sound system. Finally, there may be factors affecting the results that a professional acoustician would identify that are not obvious to the technical managers of the venue.

3.1.2 Measuring reverberation time using ISO 3382-1

As indicated, it is essential to evaluate the uncertainty of the measurement method explained in Section 3.1.1 by measuring the reverberation time in some of the participating venues using well-established methods. To assess the reverberation time in the performance spaces, the guidelines in ISO 3382-1:2009 *Measurement of room acoustic parameters - Part 1: Performance spaces* [10] were used. ISO 3382-1 proposes a method for measuring reverberation times both from interrupted noise and impulse responses.

The reverberation time was measured at six venues. Due to travel restrictions from the ongoing COVID-19 pandemic, only participating venues located in Trondheim were measured. Four venues were measured using the interrupted noise method and two venues using the impulse response method. Table 3.1 contains information of when and where the measurements took place and what excitation type was used. Five of the measurements was performed during the spring of 2021, while one was done in the summer of 2020 while working at the acoustic consulting company Brekke & Strand AS.

Venue #3 was supposed to be measured using pink noise. However, due to miscommunication, the author was not allowed to use pink noise as it would disturb the venue's neighbours. Hence, popping a balloon was used as a last resort. Previous research is mixed on the reliability of this method [11, 12, 13, 14], and as a result, discussions were had on whether to rule out the results from this particular venue. In the end, the author decided to include results from venue #3, but when assessing the results, they will not weigh as much as the other measurements.

Table 3.1: An overview measurements in this study and the type of excitation used.

#	**Venue**	**Date**	**Excitation type**
1	Dokkhuset Scene	26.02.2021	Pink noise
2	Kultursenteret ISAK Amfisalen	10.02.2021	Pink noise
3	Nidelven Bar & Scene	08.02.2021	Impulse - balloon
4	Studentersamfundet Klubben	01.03.2021	Pink noise
5	Studentersamfundet Knaus	01.03.2021	Pink noise
6	Studentersamfundet Storsalen	21.08.2020	Impulse - blank gun

In all venues, three source positions were chosen at random locations on the stage. Each source position was measured in arbitray positions in the audience area. According to ISO 3382-1, one should use an omnidirectional loudspeaker for measurements with the interrupted noise method. However, in this study, a hemi-dodecahedron loudspeaker was used which radiates sound in a hemispherical pattern when placed on the floor. Even though the loudspeaker is not omnidirectional, it is assumed to provide adequate results for these measurements. All source and receiver positions were chosen to comply with the recommendations given in ISO 3382-1.

Reverberation times were measured using the built-in function in the Norsonic Nor140 sound analyser. A measurement log of all measurements can be found in Appendix B. Table 3.2 contains an overview of the equipment used in venue #1-5 (venue #3 did not use a loudspeaker or amplifier), while Table 3.3 contains an overview of the equipment used in venue #6.

Table 3.2: Equipment used in measurements of venue #1-5.

Equipment	**Model**	**S/N**
Sound level meter	Norsonic Nor140	1404871
Microphone preamplifier	Norsonic Nor1209	14525
Microphone	Norsonic Nor1227	142202
Calibrator	Norsonis Nor1251	33299
Hemi-dodecahedron loudspeaker	Norsonic Nor275	2755173
Power Amplifier	Norsonic Nor280	2804026

Table 3.3: Equipment used in measurements of venue #6, Studentersamfundet Storsalen.

Equipment	**Model**	**S/N**
Sound level meter	Norsonic Nor140	1405688
Microphone preamplifier	Norsonic Nor1209	15549
Microphone	Norsonic Nor1225	215387
Calibrator	Norsonis Nor1251	34552
Blank gun	Smith & Wesson Chiefs Special S	I017709

3.2 Analysing Kulturrom's database

The other main objective of this thesis is to analyse the database containing measurements of concerts from participating venues. As mentioned in Chapter 2, each measurement log is uploaded automatically to a common FTP server. The content in the measurement log is thoroughly explained in Chapter 2.

Microsoft Excel was used to analyse the database, and MATLAB was used in the correlation analysis. This MATLAB code can be found in Appendix E. This part of the thesis can be seen as a continuation of the work done by Støfringsdal [3] in 2018, and Bård Støfringsdal and Jan Olav Owren were kind enough to share the VBA script used in that paper to import the measurement logs to Excel. During this study, this script has been further developed to include some more parameters.

When importing the measurement logs into Excel, the following information was included:

- name of venue, filename, artist and a comment provided by the sound engineer;
- date, start time and length of measurement;
- warning level chosen by the venue;
- calibration sensitivity in mV/Pa;
- Single value levels: Max $L_{A,Eq,15/30min}$, Max $L_{C,Eq,15/30min}$, $L_{AF,max}$, $L_{CF,max}$, $L_{Cpeak,max}$ and time above warning level given in seconds;
- averaged energy spectrum in third-octave bands from 16 Hz to 20 kHz.

The database contains 4377 concerts from 107 venues with a wide range of different events and genres. In parallel with the work done in this study, Kulturrom has made an effort to categorise all events in the database into the following genres:

- Pop/rock
- Metal
- EDM/electronica
- Urban
- Folk/world
- Jazz
- Singer-songwriter/acoustic
- Corps
- Choir
- Classical
- Theater/stand-up comedy
- DJ
- Other

When analysing the database, 2622 measurements have been specified with a genre, which leaves 1755 measurements without a genre specification. The reason why so many concerts have not been categorised into genres is that it is manual time-consuming work since the genre is not specified in the measurement log. All measurements without genre specification have been excluded in this analysis. This will significantly reduce the total number of measurements, but the information available in the database will be more relevant and precise.

Due to the large variety of events and information in the database, it is necessary to filter the data further to obtain a sub-set with relevant data. In this study, the concerts fulfilling the criteria listed in Table 3.4 were included. As seen, 621 concerts fulfilled the chosen criteria, and 50 venues are included in the subset.

Table 3.4: Criteria used in the filtration of the database, and the number of excluded concerts.

#	**Criteria**	**Excluded concerts**
1	Can not contain the word "test" in measurement info	425
2	Genres: pop/rock, jazz, singer-songwriter/acoustic	3218
3	Warning level: $L_{A,Eq,15\text{ min}}$ 102 dB	1023
4	2 mV/Pa < Calibration sensitivity > 10 mV/Pa	432
5	Max $L_{AEq@15min} \geq$ 80 dB	952
7	Length of measurement > 30 min	380
	Total amount of excluded concerts:	3756
	Included concerts:	621

The criteria chosen in this study is somewhat stricter than what Støfringsdal used in 2018. Upon the analysis of the database, it became clear that some extra criteria were needed. For instance, a criterion regarding the calibration sensitivity was necessary. As seen in Figure 3.4 there are some outliers in the measurements when it comes to calibration sensitivity. In addition, we see that many measurements have a calibration sensitivity of 10.0 mV/Pa. Apparently, this is the default value that the measurement software is set up with, indicating that these measurements are not calibrated.

During this work, the author was notified by supervisor Jan Olav Owren that he had performed a test to see how the calibration sensitivity varies among different microphones. Owren received a measurement system from Kulturrom with three similar microphones. After a simple test, he found the following calibration sensitivity for the three microphones: 4.35, 4.99 and 7.18 mV/Pa. This indicates that the calibration sensitivity will vary from system to system, hence why criterion #4 was used.

Another variation from the criteria used in the study from 2018 is criterion #5 in Table 3.4. Støfringsdal set this limit to 90 dB. However, after inspecting the database, it seemed this limit would exclude many valid measurements. Consequently, the limit was lowered to 80 dB.

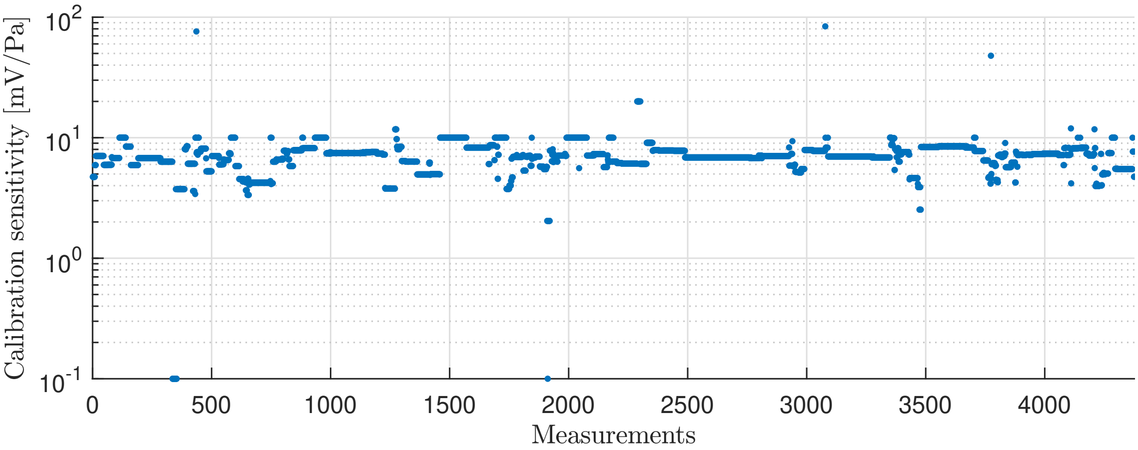


Figure 3.4: An overview of the calibration sensitivity in all measurements.

Chapter 4

Theory

In this chapter, we will establish the basis to understand and interpret the results shown in Chapter 5. At first, we will look at the theory behind the measurements and analysis of the reverberation time in this study before we look at some background theory needed to understand the analysis of the dataset in the FTP server.

4.1 Reverberation time

Throughout the years, many parameters have been developed to describe and quantify the acoustical properties of rooms. The reverberation time was previously regarded as the primary acoustic parameter. While other parameters such as early/late energy ratios, interaural cross-correlation functions and relative sound pressure levels are needed for a thorough evaluation of the acoustical properties of rooms, the reverberation time is still regarded as a significant parameter [10].

Measurements of room impulse responses have been of interest for a considerable period. Until Schroeder proposed a measurement method using the Maximum-Length Sequence (MLS) method in 1979, the most common way to measure room impulse responses was by using impulsive sound sources such as popping balloons or firing with blank guns [15]. Since then, many studies have explored the strengths and weaknesses of the MLS method [16, 17, 18, 19].

Not long after Schroeder introduced the MLS technique, other methods were introduced, e.g., the Inverse Repeated Sequence (IRS) technique [17], and the time-stretched pulse technique [20]. The theory behind these techniques is beyond the scope of this study. However, using FFT-based measurements for finite-length excitation signals to find an impulse response was introduced in a famous paper by Farina in 2000 [21]. The idea of using sweeps to deconvolve an impulse response was introduced in 1994 [22], but Farina proposed a new deconvolution method. The theory from Farina's paper will be presented in the following section.

4.1.1 Measuring impulse responses using Fast Fourier Transform

Imagine a so-called linear, time-invariant (LTI) system with a single input, $x(t)$, generating a single output signal, $y(t)$. Some noise might be generated in this system, which is usually assumed to be uncorrelated with the output signal. In such cases, $y(t)$ is gained by the convolution of the systems impulse response, $h(t)$, and $x(t)$

$$y(t) = n(t) + x(t) \circledast h(t) \tag{4.1}$$

where $n(t)$ describes the noise generated in the system. An illustration of such systems can be found in Figure 4.1. As both $x(t)$ and $y(t)$ are periodic, the input and output can be related by a circular convolution. If the signal-to-noise ratio (SNR) is sufficiently high, we can deconvolve $h(t)$ using Equation 4.2.

$$h(t) = \text{IFFT}\left[\frac{\text{FFT}(y(t))}{\text{FFT}(x(t))}\right] \tag{4.2}$$

In MATLAB, Farina's method can be implemented in the following way:

```
%Defining length of fft
n = 2^(nextpow2(max([length(outputsig) length(inputsig)])));

%fft of both input and output signal
x = fft(inputsig,n);
y = fft(outputsig,n);

%Deconvolution and ifft.
h = real(ifft(y./x));
```

Since both $x(t)$ and $y(t)$ are real-valued, $h(t)$ must also be real-valued. However, MATLAB will give a tiny imaginary part when the inverse fast Fourier transform is calculated due to its fine precision. Hence, it is necessary to use the `real` function in MATLAB.

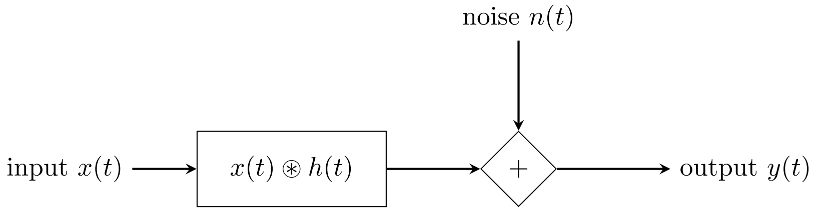


Figure 4.1: A basic single input/output LTI system with noise added to the output signal.

According to Farina, this method can use several excitation signals as long as it is wide-band, deterministic and periodic [21]. A popular excitation signal, and the one used in this study, is the exponential sine sweep which can be defined by [23]:

$$x(t) = \sin\left[\frac{\omega_1 T}{\ln \frac{\omega_2}{\omega_1}}\left(e^{\frac{t}{T}\ln\frac{\omega_2}{\omega_1}} - 1\right)\right] \tag{4.3}$$

where T is the length of the sweep in seconds, while ω_1 and ω_2 represent the start and stop frequency, respectively.

We are interested in measuring the impulse response while removing the artefacts caused by noise, the loudspeaker's non-linear behaviour, and time variance. According to Farina [23], the exponential sine sweep provides a good solution to these three problems: SNR is higher than an MLS signal, non-linear effects are separated from the linear response, and the use of one long sweep avoids trouble regarding time variance in the system.

Although the method using FFT-based deconvolution of finite excitation signals has many advantages compared to other methods, some challenges are associated with it. Since its introduction at AES-Paris in 2000, the method has been a subject of many studies, including the JAES papers of Müller/Massarani [24] and Stan et al. [14]. Based on previous research in these studies, some known limitations/problems with the exponential sine sweep method include [23]:

- measurements are sensitive to pulsive noises;
- skewing of the impulse response when the playback and recording devises are not synced;

- pre-ringing before the arrival of the direct sound at low frequencies;
- cancellation of high frequencies at the end of the tail when averaging synchronously;
- time-smearing of the impulse response if amplitude-based pre-equalisation of the sweep was employed.

After researchers recognised these problems, they have been explored, and several solutions have been proposed. However, we will not look further into this in the current study.

4.1.2 Calculating reverberation time from impulse responses

Once the room impulse response is measured or calculated, the general procedure for calculating the reverberation time from a measured room impulse response is done using the following steps [25]:

1. Truncation of the impulse response at the start by starting where the signal first rises significantly above the background noise but is more than 20 dB below the maximum [10].
2. Filter the impulse response in (third-)octave bands.
3. Truncation of the impulse response at the end at a different point in each frequency band.
4. Squaring the impulse response
5. Optional step: compensate for the decay energy lost in step three
6. Backwards integration of the impulse response, and converting to dB
7. Using linear regression to find the reverberation time. T_{20}: -5 to -25 dB and T_{30}: -5 to -35 db from the maximum.

In Figure 4.2 we see an example of an impulse response calculated from one of the exponential sine sweep measurements in this study. In this impulse response, we can observe that the initial level is very high. When using non-omnidirectional loudspeakers, such as a PA system, the direct sound will be loud compared to the reflections in the room. Several studies have explored how the directivity of the sound source affects the measurements of room acoustic parameters [26, 27, 28]. In theory, one could expect that the reverberation time will be shorter if the initial peak of the impulse response is more than 5 dB higher than the decay curve. However, Adelman-Larsen et al. [26] could not find a significant difference in the reverberation time in the audience area, but they saw a significant difference in the stage area.

Furthermore, in Figure 4.3 we see the initial part of two decay curves and their respective Schroeder curves in the 125 and 8000 Hz octave band. The Schroeder curve is equivalent to step 6 in the steps listed above and is based on backward integration of the impulse response [29]. At 8 kHz, we can observe that the Schroeder curve is flat initially and has a steep drop-off after 0.01 seconds. A similar phenomenon can not be observed at 125 Hz. This effect is likely due to the loudspeaker's directivity: it is common for PA systems to have a high directivity at high frequencies and vice versa for low frequencies [30].

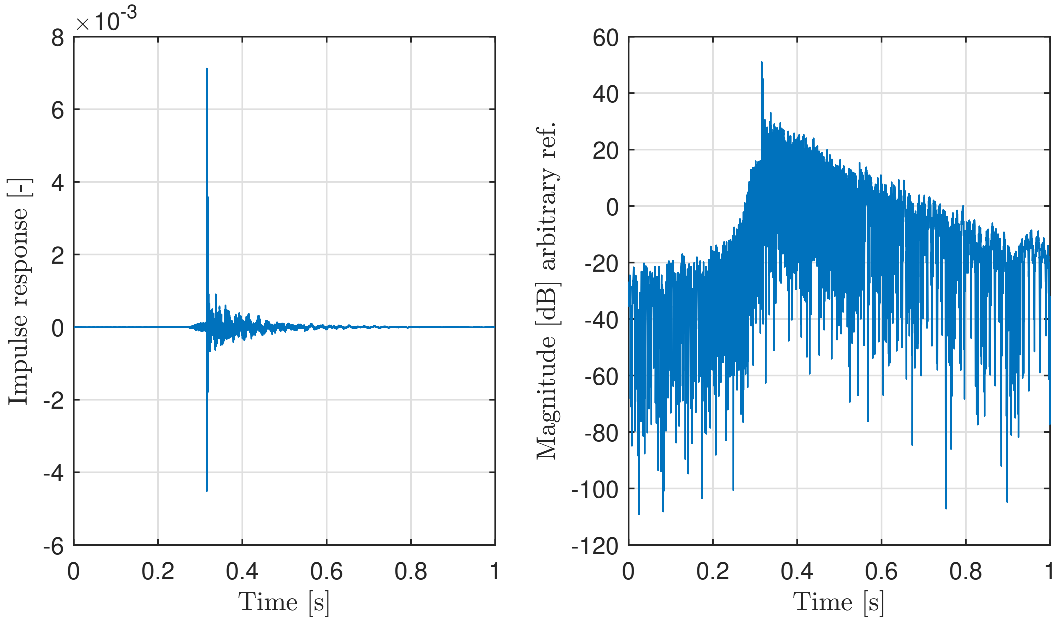


Figure 4.2: An example of an impulse response generated from one of the measurement logs with both a linear and logarithmic y-axis.

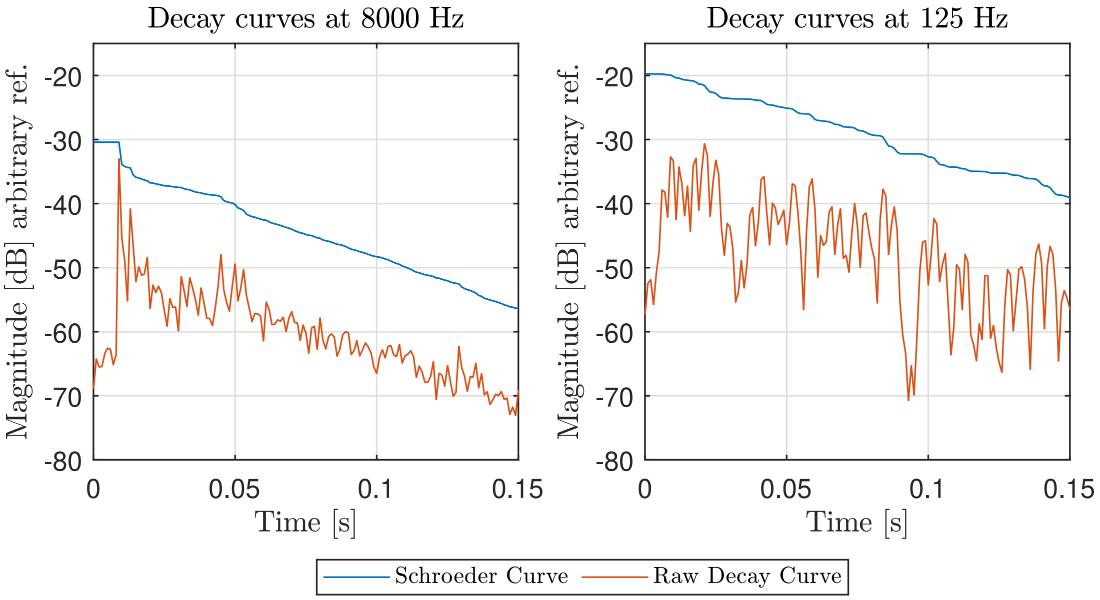


Figure 4.3: Example of a typical decay curve generated in ODEON from one of the impulse responses. Note: only the initial part of the decay is shown to illustrate the effect of directivity on the impulse response.

4.1.3 Measuring reverberation time using the interrupted noise method

Measurements of reverberation time using the interrupted noise method have been referred to as the classical method [31]. This method is based on a simple technique: an omnidirectional sound source is switched on with broadband noise until the room has a steady level. At the time t_0, the sound source is switched off, and the decay in the room is observed. This is illustrated in Figure 4.4.

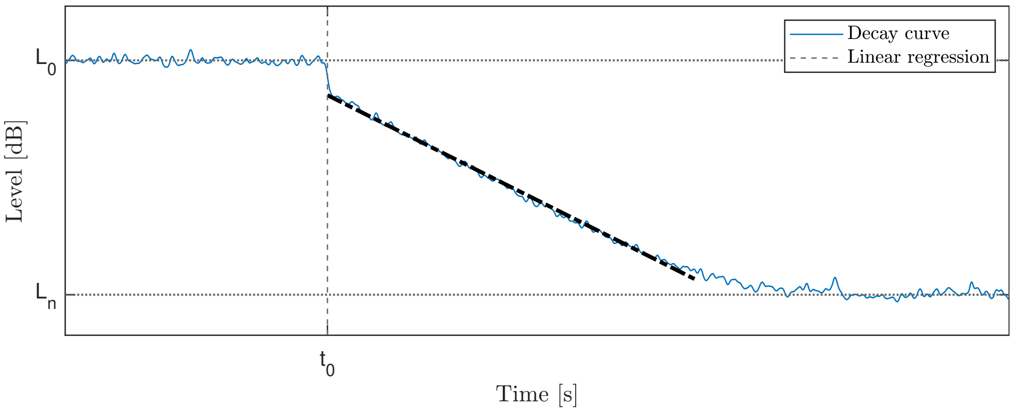


Figure 4.4: Illustration of reverberation decay from the interrupted noise method.

As mentioned, it is common to use broadband noise to determine the reverberation time with this method. When investigating the frequency scale in octave bands, we see that the bandwidth decreases for lower frequencies, which amounts to -3 dB per octave. Hence, a popular excitation signal is pink noise, which is boosted in low frequencies and reduced in high frequencies by 3 dB per octave [32].

When computing reverberation time from the decay curve, ISO 3382-1 suggests two different values: T_{20} which is derived from the time where the decay curve reaches 5 dB to 25 dB from the initial level, and T_{30} may be used for when the decay curve reaches 5 dB to 35 dB below the initial level. Both T_{20} and T_{30} refers to a 60 dB drop in level.

Uncertainty evaluation is an important part of acoustic measurements. Due to the random nature of the excitation signal, the uncertainty of the measurements is heavily affected by the number of averages performed [10]. ISO 3382-1 describes a way of calculating the standard deviation for T_{20} and T_{30} using the following formulas:

$$\sigma(T_{20}) = 0.88T_{20}\sqrt{\frac{1+1.9/n}{NBT_{20}}} \tag{4.4}$$

$$\sigma(T_{30}) = 0.55T_{30}\sqrt{\frac{1+1.52/n}{NBT_{30}}} \tag{4.5}$$

where B is the bandwidth, in hertz, n is the number of decays measured in each position, and N is the number of measurement positions. For octave bands, $B = 0.71f_c$, while for one-third octave bands, $B = 0.23f_c$. f_c is the centre frequency of each band in hertz. According to ISO 3382-1, measurements in octave bands have lower uncertainty than one-third octave band measurements with the same number of measurement positions.

Moreover, ISO 3382-1 suggests that for practical evaluation of the measurement uncertainty using the integrated impulse response method, it can be considered as being of the same order of magnitude as using an average of $n = 10$ measurements in each position with the interrupted noise method.

To assess the difference between reverberation time obtained with ISO 3382-1 and through the ESS analysis, it can be beneficial to define a parameter for the error, e. In this study, we assume that measurements using ISO 3382-1 gives an accurate estimation of reverberation time, so the author proposes the following relationship to determine e:

$$T_{\text{ISO 3382-1}} = T_{\text{ESS}} + e \tag{4.6}$$

where $T_{\text{ISO 3382-1}}$ and T_{ESS} represents the reverberation time obtained in the two respective methods. Nonetheless, the author does not imply that reverberation time gained with ISO 3382-1 has zero error.

When calculating e, reverberation times must be given in the same type of octave bands. In this study, measurements using ISO 3382-1 were made in one-third octave bands, but in the analysis of the room impulse responses gained with ESS, it was only possible to obtain reliable results in octave bands. Therefore, conversion from one-third octave bands to octave bands was needed. This conversion has received limited attention in literature. The author only found one source on the subject: NS 8173:1987 *Building acoustics - Measurement of reverberation time in rooms*[33], and it suggests the following formula:

$$T_{\text{oct}} = T_3 - \frac{2T_3 - T_2 - T_1}{5} + \frac{(2T_3 - T_2 - T_1)^2}{10T_3} \tag{4.7}$$

where $T_3 > T_2 > T_1$. If $T_3 > 2\ T_1$, T_1 is replaced by T_3. According to NS 8173, this conversion method has a margin of error within ±10 %. Currently, this standard is withdrawn, and it must be said that any references do not back this formula. In this process, the author analysed this conversion compared to simple arithmetic averaging of third octave bands. Results indicate that the method in NS 8173 might give a slightly higher reverberation time at low frequencies. However, due to a lack of other options, it has been used in the analysis in this study.

4.2 Theory behind the analysis of Kulturrom's database

In this section, the author will introduce the theoretical underpinnings in the analysis of Kulturrom's database. As a reminder, a thorough background of Kulturrom's project, including a detailed description of what parameters are logged, is provided in Chapter 2. As the reader is expected to understand fundamental concepts in acoustics such as time weighting, time-averaging, frequency weighting, and so on, we will not go further into these subjects. However, other important subjects will be explored in the current section.

4.2.1 Sound level limits

Many countries have regulatory and legislative approaches to manage sound levels and minimising the risk of hearing damage among workers and attendees at concerts [34]. In 2011, a working group was led by the Health Directorate of Norway to develop national guidelines to prevent hearing damage among attendees and employees at concerts with amplified music, entitled "Music and health: Guide to organisers and municipalities IS-0327" [9]. The proposed limit values in this guideline are found in Table 4.1.

Table 4.1: National guidelines for sound level limits in concerts for amplified music [9].

	$L_{A,Eq,30min}$	$L_{C,peak}$
Warning limit	92 dB	130 dB
Absolute limit	99 dB	130 dB

However, in Norway, it is up to the local authorities to impose the regulations at concerts. Therefore, many concert venues and festivals in Norway do not have sound level limits [35]. As mentioned in Chapter 2, Kulturrom has proposed two different limit values to the participating venues in their ongoing project: $L_{A,Eq,15min} \leq 102$ dB **or** $L_{A,Eq,30min} \leq 99$ dB.

The actual sound level exposure of attendees and employees in concerts with amplified music has received limited attention in literature. Although some attempts have been made to address this issue [3, 35, 36, 37, 38], it is still necessary to broaden the knowledge of sound exposure at concerts. In a study by Tronstad and Gelderblom [35], the sound exposure during two outdoor Norwegian music festivals were investigated. One of the two festivals were not regulated by any sound limit guideline, and results showed that sound levels were higher at the unregulated festival. Moreover, this study showed that front-of-house measurements reliably predict participant exposure.

4.2.2 Acoustic properties

In a study from 2010 by Adelman-Larsen et al. [26], correlations between subjective and objective parameters were investigated for 20 venues for rock and pop music. They found that clarity, including bass frequencies down to 63 Hz, is important for the general impression of the venue's acoustics. They also saw that the best rated venues had approximately frequency-independent reverberation times from 0.6 to 1.2 s, and the worst rated halls had significantly higher reverberation times in the 63 and 125 Hz octave bands. Furthermore, they measured reverberation time with a standing audience, and results revealed that the audience absorbs about five times the energy in mid-/high-frequency bands as opposed to the low-frequency bands.

In the present study, we will investigate correlation between the same objective parameters as Adelman-Larsen et al. did in 2010 and the mean max $L_{A,Eq,15\text{ min}}$ values for each venue. The following parameters are included in the study: T_{20} with subscripts W for wideband (63-2000 Hz), B for bass (63-125 Hz), and M/T for mid/treble (250-2000 Hz). Moreover, we will look at the bass ratio, BR, which Adelman-Larsen et al. defined as the ratio of T_{20}(63-250 Hz) and T_{20}(500-2000 Hz) [26], EDT (63-2000 Hz), and finally D_{50} (63-2000 Hz). All parameters are derived in ODEON from the impulse response measured at the mix position with ESS as excitation signal played through the venue's PA system.

BR, or bass ratio, was defined by Beranek in 1962 as a way to define the acoustic quality of a room [39]. Beranek originally thought that the bass ratio could be used to obtain a rating level of the venue, and stated that "A hall lacks warmth when the reverberation times are lower at low frequencies (75 to 350 Hz) than at mid-frequencies (350 to 1400 Hz), i.e. low BR" [40]. Nevertheless, newer studies revealed that bass ratio can not be used to quantify the acoustic perception of a concert hall in terms of the perceived strength of bass sound [41, 42]. That being said, a review of the acoustic quality of the participating venues is beyond the scope of this study. Here, the author will use BR as a way to quantify the reverberation time in a venue.

EDT, or early decay time, is derived from 0 to −10 dB of the decay curve of a room impulse response and can be described as the subjectively perceived reverberance [10]. The decay time is calculated from the slope as the time required for a 60 dB decay. According to ISO 3382-1, EDT is subjectively more important and related to perceived reverberance, while T is related to the physical properties of the auditorium.

$\mathbf{D_{50}}$, or definition, is derived from the early (0 - 50 ms) to total energy ratio and is a measure of perceived clarity of sound given by the following equation [10]:

$$D_{50} = \frac{\int_0^{0.050} p^2(t)\mathrm{d}t}{\int_0^{\infty} p^2(t)\mathrm{d}t} \tag{4.8}$$

where p is the measured energy in an impulse response. As far as the author know, no previous research has investigated the correlation between these parameters and sound levels on concerts.

In addition to T, BR, EDT and D_{50}, other properties regarding room geometry will be explored. The Norwegian standard NS 8187:2014 "Acoustic criteria for rooms and spaces for music rehearsal and performance" [43] provides guidelines when designing new rooms and spaces for music performance in Norway. It states a clear connection between the intended use of a room and the different needs for room size, reverberation time, room height and geometry. The standard sets different recommendations for amplified music, acoustical loud music, and acoustical quiet music. Here, we will focus on amplified music.

Within amplified music for performance halls, the standard gives different recommendations for club stages and halls and states that the following conditions are important to take care of [43, sec. 4.1]:

- appropriate room size (net volume and area);
- adequate bass absorption;
- short reverberation time, smooth reverberation time curve as a function of frequency;
- smooth frequency response;
- control of repeated reflections, inclining of surfaces, diffusion and sound diffusing elements in order to avoid echoes;
- not too prominent room resonance;
- good sound insulation to adjacent rooms.

The criteria for performance spaces for amplified music in NS 8178 are based on [26].

Moreover, the standard specifies numeric values for properties such as average net room height, net volume, net area, stage area, acoustic treatment, reverberation time, and background noise level. As a result, there are many properties the acoustician need to handle when designing spaces using NS 8178.

Studies on whether these properties affect the sound level in concerts are limited in literature. Hence, in the present study, the correlation between sound level and some of these properties will be explored.

As mentioned, the properties listed above will be checked for correlation with the mean max $L_{A,Eq,15\text{ min}}$ level for all concerts in the filtered data set in each venue. In this analysis, the max $L_{A,Eq,15\text{ min}}$ level in each concert is averaged arithmetically to find a global mean value for each venue. Arithmetic average is used better to represent the variety of sound levels at concerts. If they were energy averaged, the loudest concerts would have an artificially high effect on the results, especially due to the dominance of low frequency energy at Pop/Rock concerts.

4.2.3 Statistical analysis

When assessing complex data sets to determine if different parameters are related, statistical analysis is needed. For a simple data set of two variables, x and y, linear regression and Pearson's correlation coefficient, r, can be helpful [44].

The following equations are used to determine an equation for a straight-line model, $y = a + bx$ [45]:

$$b = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{4.9}$$

$$a = \overline{y} - b\overline{x} \tag{4.10}$$

where overlined variables represents its average value. In MATLAB, these coefficients can be found using the `polyfit` function. Furthermore, the correlation coefficient r, often referred to as Pearson's correlation coefficient was developed by Karl Pearson in the late 19th century [46]. r gives a measure of linear association between two variables and is found by:

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{4.11}$$

In MATLAB, r can be found using the `corrcoef` function. Another parameter that can be found using `corrcoef` is the probability value, p, which can be used to test the null hypothesis, H_0. The null hypothesis proposes that there are neither a statistical relationship nor statistical significance between two population parameters [47]. p represents the probability for exclusion of the null hypothesis. In this study, $p < 0.05$ is considered statistically significant.

Chapter 5

Results

This chapter presents the results of this study. At first, we will start with results gained in the reverberation time measurements before key findings from the database analysis are presented. Raw data from the measurements and the impulse response analysis is found in Appendix B and C, respectively.

5.1 Reverberation time measurements

This section outlines the results of the comparison between reverberation time gained from FFT-based deconvolution of recordings in one receiver position of exponential sine sweeps (ESS) played through a PA system, with reverberation time measurements using ISO 3382-1. The analysis of impulse responses is done with two software: ODEON and EASERA. Figure 5.1 presents the error in using recorded ESS compared to measurements using ISO 3382-1, as defined in Equation 4.6. Note that reverberation times gained from using ISO 3382-1 have been converted to octave bands by Equation 4.7, and EASERA only calculates reverberation time down to the 125 Hz octave band.

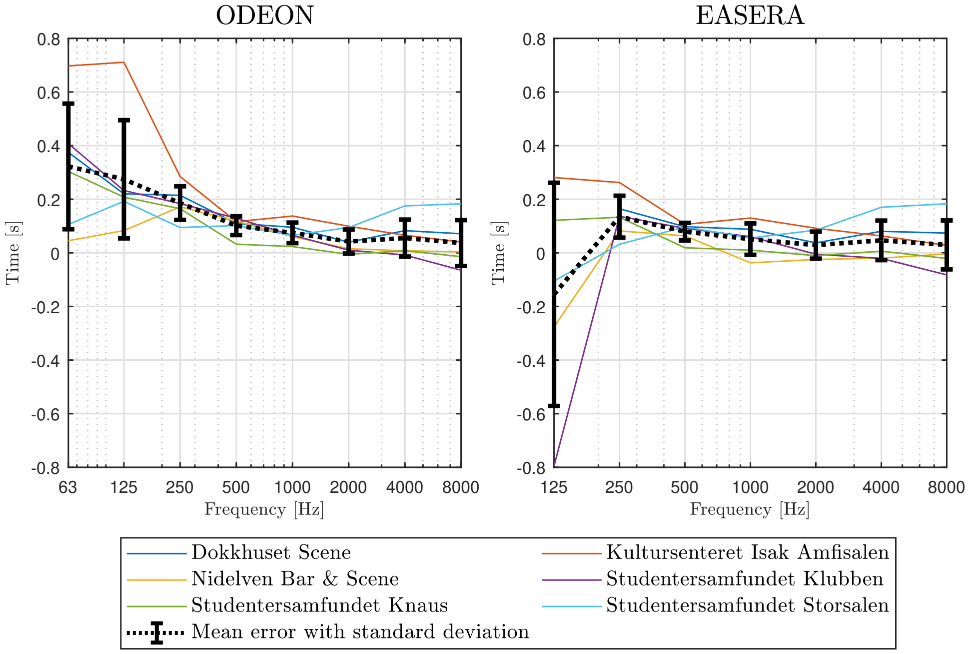


Figure 5.1: An overview of the error obtained when finding reverberation time from recordings of ESS through a PA system in one receiver position compared with measurements using ISO 3382-1.

As seen in Figure 5.1, there is a substantial difference between the analysis from ODEON and EASERA at low frequencies. However, one can observe that the mean error and standard deviation above 250 Hz are similar in both software. It is interesting to note that the standard deviation is lowest for mid-frequencies and increases for high and low frequencies, and that in general $e > 0$.

In Figure 5.2 we see measurements using ISO 3382-1 and results from the analysis in ODEON and EASERA of FFT-based deconvolution of room impulse responses gained from recordings of ESS played through a PA system in one receiver position. Notice that results from measurements have not been converted to octave bands in this figure. In general, we see that ODEON and EASERA give very similar results above 250-500 Hz. One exception from this is venue #6. At low frequencies, the uncertainty is higher. An evaluation of what software is most reliable is beyond the scope of this study. Still, as a general statement, one can say that the difference at low frequencies between the two software can be seen as a result of the high uncertainty in the measurement method.

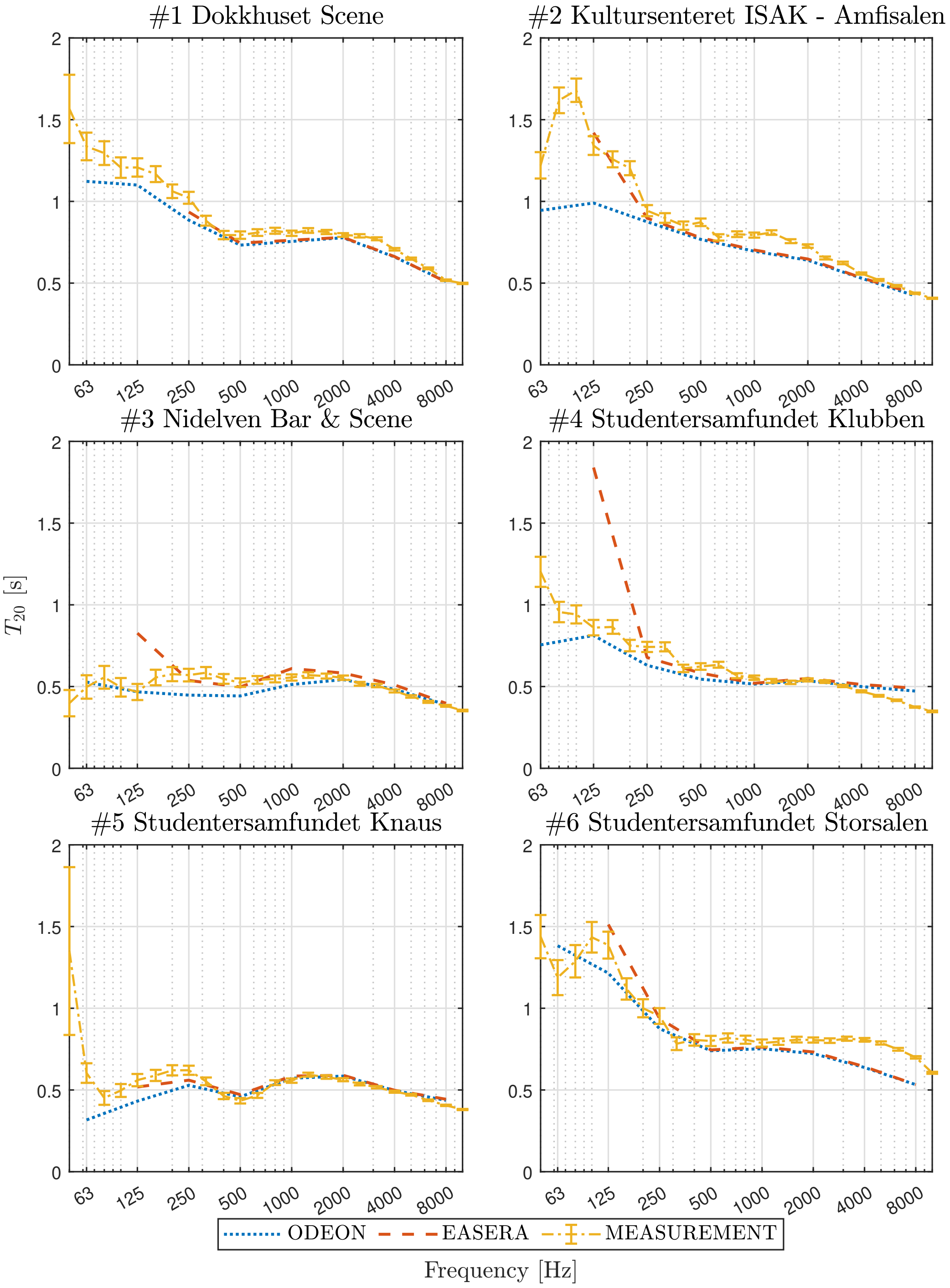


Figure 5.2: An overview of all reverberation times gathered in all six venues, both from measurements using ISO 3382-1 and analysis in ODEON and EASERA of room impulse responses gained from ESS through a PA system in one receiver position.

5.2 Analysis of Kulturrom's database

As mentioned in Section 3.2, this part of the study is based on a filtered data set containing 621 concerts in 50 venues. All information regarding sound levels is anonymised to maintain venues and artists privacy. In Figure 5.3 we see a bar graph of the max $L_{A,Eq,15\text{ min}}$ value obtained in each concert. One can observe that many concerts lie close to the warning level of $L_{A,Eq,15\text{ min}}$ 102 dB. Moreover, 14 % exceeded the warning level indicated by the red bars.

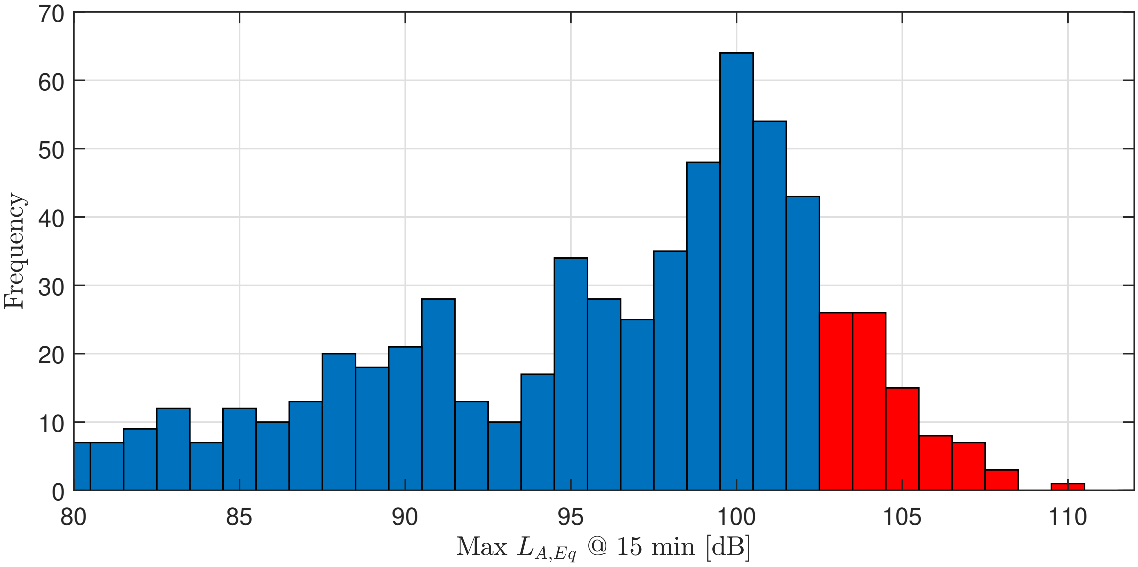


Figure 5.3: Bar chart of the maximum $L_{A,Eq,15\text{ min}}$ values obtained in each concert in the filtered data set. Red bars indicate values above the chosen warning level.

Table 5.1 presents differences between key parameters in this study. As indicated by the difference between $L_{AF,max}$ and Max $L_{A,Eq,15\text{ min}}$, the average dynamic span is between 10-13 dB. It is interesting to note that if a concert is kept within the warning level, one can still expect to experience $L_{CF,max}$ ≈ 122 ± 4.3 dB. In general, one can say that the findings in Figure 5.3 and Table 5.1 are consistent with the results reported by Støfringsdal [3].

Table 5.1: Differences between key parameters, including results from Støfringsdal's paper from 2018 [3]. μ represents the average and σ the standard deviation.

	Results		**Støfringsdal [3]**		**Deviation**	
Parameter	μ [dB]	σ [dB]	μ [dB]	σ [dB]	μ [dB]	σ [dB]
$L_{AF,max}$ - Max $L_{A,Eq,15\text{ min}}$	12.7	3.1	12.1	3.1	0.6	0.0
$L_{CF,max}$ - Max $L_{C,Eq,15\text{ min}}$	10.6	3.0	10.0	2.7	0.6	0.3
$L_{CF,max}$ - Max $L_{A,Eq,15\text{ min}}$	19.7	4.3	20.5	4.1	-0.8	0.2
$L_{C,Eq,15\text{ min}}$ - Max $L_{A,Eq,15\text{ min}}$	9.1	3.5	10.5	3.6	-1.4	-0.1

Figure 5.4 shows the average energy spectrum in one-third octave bands divided into the included genres: pop/rock, jazz, and singer-songwriter/acoustic. The sound levels are calculated based on energy averaging of all included concerts. We can observe that the overall sound level is different in the three genres, with pop/rock being the loudest. In addition, we see a general trend that there is a maximum around 50 Hz, and above that, the sound level decreases with increasing frequency. Although, singer-songwriter/acoustic also has a local maximum at 315 Hz.

From Figure 5.4 we can realise that a substantial part of the energy in amplified music is in the 63 Hz octave band. This shows that it is important to include the 63 Hz octave band when considering the acoustic properties of venues for amplified music. In addition, these results can be useful when designing sound insulation in such venues.

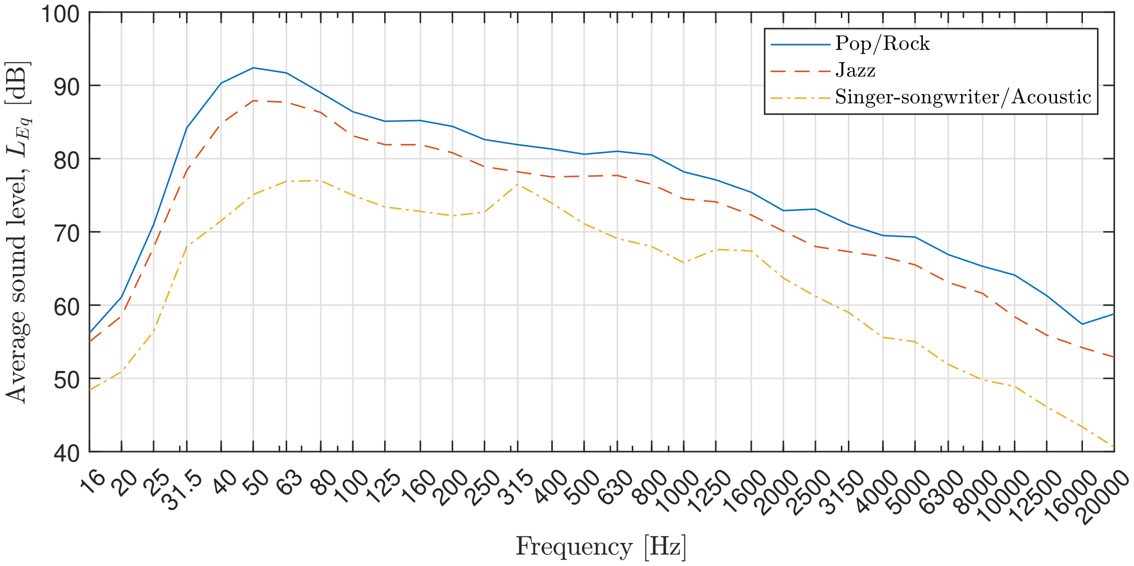


Figure 5.4: Average energy spectrum for all included concerts, divided in genres and given in one-third octave bands from 16 Hz to 20 kHz.

5.2.1 Correlation between acoustic properties, venue geometry and sound level

As stated, a survey was sent out to all participating venues in 2018. This survey, including data such as room volume and ceiling height, has been used in this study. A total of 54 participants answered the survey, and to complement the survey results, `www.scenerommet.no` and websites of participating venues have been looked through to find metadata from venues that did not answer the survey. A complete list of all included venues and their respective geometry data is found in Appendix A.

Table 5.3 features a complete list of the participating venues that also recorded the ESS in one position played through the PA system, including key information about geometry, audience capacity and acoustic properties derived from the room impulse responses. Some venues have recorded the ESS several times in one position, and in those cases, the results have been arithmetically averaged. Note that only 14 of these 28 venues were included in the filtered data set.

Correlation coefficients and p-values were calculated between the mean max $L_{A,Eq,15\text{ min}}$ level of each venue and hall volume, room height, audience capacity, $T_{20,W}$ (63-2000 Hz), $T_{20,B}$ (63-125 Hz), $T_{20,M/T}$ (250-2000 Hz), EDT (63-2000 Hz), D_{50} (63-2000 Hz), and finally BR which is the ratio of T_{20} (63-250 Hz) and T_{20} (500-2000 Hz).

As seen in Table 5.2, significant correlations (marked in bold) were found between the mean max $L_{A,Eq,15\text{min}}$ level and hall volume, room height, D_{50}, and BR. No significant correlation was found for audience capacity, $T_{20,W}$, $T_{20,B}$, $T_{20,M/T}$, or EDT. No scatter plots are shown where the mean max $L_{A,Eq,15\text{min}}$ level are included to maintain privacy of each venue.

Table 5.2: Correlation coefficients and p-values between the mean max $L_{A,Eq,15\text{min}}$ level of each venue and parameters found by analysing recordings of ESS in one receiver position played through the PA system of each venue. Significant correlations ($p < 0.05$) are marked in bold.

	Volume	Room heigth	Audience capacity	$T_{20,W}$	$T_{20,B}$	$T_{20,M/T}$	EDT	D_{50}	BR
Sample size	32	41	44	14	14	14	14	14	14
r	**-0.43**	**-0.51**	-0.12	-0.40	-0.50	-0.26	-0.44	**0.55**	**-0.62**
p	**0.013**	**0.001**	0.425	0.161	0.069	0.379	0.118	**0.042**	**0.018**

5.2.2 Correlation between $T_{20,W}$ and venue volume

To supplement the results on sound level data, correlation between hall volume and $T_{20,W}$ was checked. In Figure 5.5 we see a scatter plot of this relation as well as a least squares regression line. As seen, $r = 0.84$ and $p \ll 0.01$, which means there is a strong significant correlation. The equation for the regression line is:

$$T_{20,W} = 0.61 \text{ s} + 7.68 \cdot 10^{-5} \ V \text{ s/m}^3 \tag{5.1}$$

where V is the volume of the hall in cubic metres. In comparison, Adelman-Larsen et al. found the following relationship: $T_{30} = 0.55 \text{ s} + 1.04 \cdot 10^{-4} \ V \text{ s/m}^3$, but this equation is also based on subjective ratings of the venues [26].

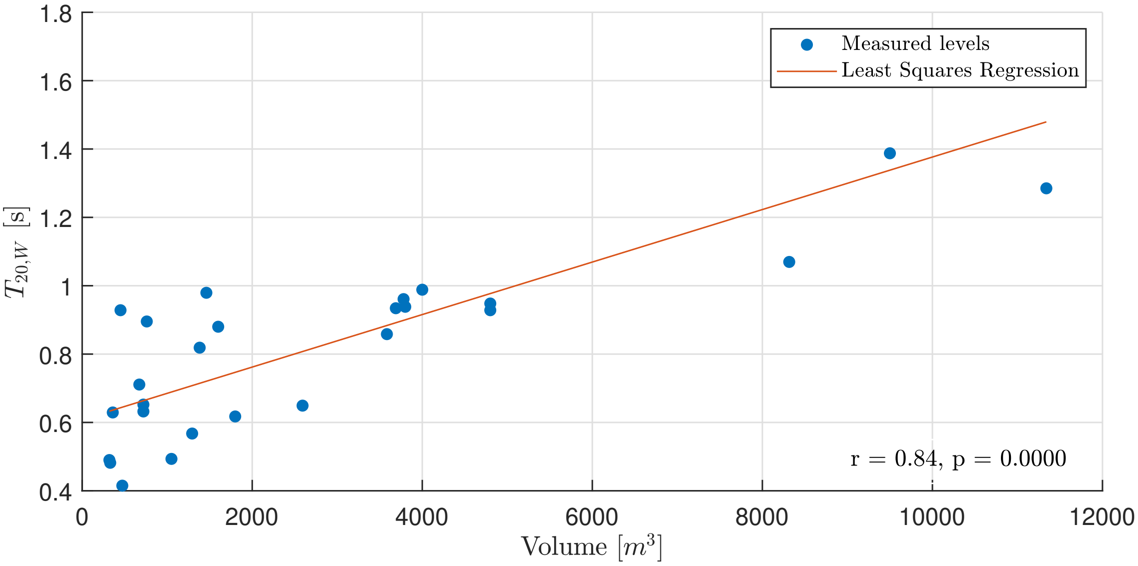


Figure 5.5: T_{20} found from analysis of recordings of ESS played through the PA in one receiver position from 63 Hz to 2 kHz vs hall volume for 27 participating venues. The line shows a linear regression of reverberation time as function of volume.

Table 5.3: Details of the 28 venues that has recorded the ESS that was sent out in the survey from 2018. Note that some venues may have been renovated since this survey was sent out.

Venue	Volume [m^3]	Room height [m]	Audience capacity	$T_{20,W}$ [s]	$T_{20,B}$ [s]	$T_{20,M/T}$ [s]	EDT [s]	D_{50}	BR
Blå Grotte	4800	10	451	0.9	1.2	0.8	0.8	0.7	1.6
Cosmopolite	4000	8	700	1.0	1.1	1.0	0.8	0.8	1.0
Dokkhuset Scene	760	4	450	0.9	1.1	0.8	0.8	0.6	1.4
Fana Kulturhus	3584	8	490	0.9	1.2	0.7	0.6	0.8	1.5
Fosnavåg Konserthus	3689	7	490	0.9	1.4	0.7	0.7	0.8	1.8
Hamar Kulturhus - Kirsten Flagstad	8316	14	500	1.1	1.5	0.9	0.7	0.8	1.7
Iris Scene	720	5	310	0.7	0.6	0.7	0.4	0.8	0.8
Jernvaren	360	2.5	200	0.6	0.9	0.5	0.5	0.8	1.6
KICK Nattklubb & Scene	2592	6	700	0.6	0.6	0.7	0.6	0.8	0.8
Kultursenteret ISAK - Amfisalen	1382	6	175	0.8	1.0	0.7	0.6	0.8	1.3
Live & Rock Cafe	-	-	-	0.7	0.6	0.7	0.6	0.6	0.8
Nasjonal Jazzscene	672	4	300	0.7	0.7	0.7	0.5	0.8	1.1
Nidelven Bar & Scene	320	2	200	0.5	0.5	0.5	0.4	0.8	1.0
Norges Handelshøyskole - Aulaen	3800	10	650	0.9	0.9	0.9	0.7	0.7	1.0
Parkteatret	1050	5	500	0.5	0.7	0.4	0.4	0.8	1.5
Riksscenen - Hovedsalen	3780	10	666	1.0	1.5	0.7	0.7	0.8	1.8
Sandnes Kulturhus - Storsalen	9120	12	666	1.6	2.3	1.3	0.9	0.8	1.7
Stavanger Konserthus - Zetlitz	9500	19	1900	1.4	1.7	1.2	1.1	0.6	1.3
Stormen Konserthus - Lille sal	1600	8	240	0.9	1.3	0.7	0.5	0.8	1.6
Stormen Konserthus - Sinus	1800	8	440	0.6	0.7	0.6	0.4	0.8	1.2
Stormen Konserthus - Store sal	11340	18	940	1.3	1.4	1.2	1.0	0.8	1.0
Studentersamfundet - Klubben	720	3.5	300	0.6	0.8	0.6	0.6	0.7	1.4
Studentersamfundet - Knaus	330	5	150	0.5	0.4	0.5	0.5	0.8	0.8
Studentersamfundet - Storsalen	5000	13	1000	0.9	1.3	0.8	0.5	0.8	1.6
Studenthuset City Scene	1294	3.85	350	0.6	0.7	0.5	0.4	0.9	1.4
Støperiet Scene	2520	6	800	0.9	1.1	0.8	0.9	0.6	1.3
Tvibit Ungdomshus	472	3.5	150	0.4	0.4	0.4	0.4	0.8	0.9
Vulkan Arena	1461	5.7	600	1.0	1.3	0.8	0.8	0.7	1.5

Chapter 6

Discussion

In this chapter, we will discuss the findings presented in Chapter 5. As before, the chapter is split into two main parts: one about the reverberation time measurements and another about the analysis of Kulturrom's database. The author will also assess the strengths and limitations associated with the study.

6.1 Reverberation time measurements

In Figure 5.1 and 5.2 we saw that the uncertainty in using recordings in one receiver position of ESS played via a PA system is a function of frequency. In general, one can claim that the uncertainty is acceptable above 250 Hz. There are many possible reasons behind these results, and we will discuss some of them below.

A trivial reason why the uncertainty is high at low frequencies is that the ESS was only recorded at one single point in each venue. In comparison, the standardised measurements use receiver positions in random locations throughout the audience area. According to wave theoretical room acoustics, the low number of modes at low frequencies will cause uneven energy distribution in the room. Hence, it is necessary to measure various positions in the room to get a high accuracy global estimate of the reverberation time at low frequencies.

A recurrent problem when dealing with the impulse responses in this study was that the signal-to-noise ratio (SNR) is somewhat limited. This was especially apparent when calculating reverberation time in one-third octave bands at low frequencies. The bandwidth is 71 % of the centre frequency for an octave filter, while in third-octave bands, the bandwidth is 23 % of the centre frequency. This means that at 100 Hz in one-third octave bands, the bandwidth is 23 Hz, while at 10 kHz, it is 2.3 kHz. Hence, we will only measure one-hundredth of the energy at 100 Hz compared to 10 kHz. This is part of the reason why it is hard to get reliable results in one-third octave bands at low frequencies. A solution to this might be to increase the length of the ESS, as this will cause a higher SNR [23]. That being said, for the intended use of this method, octave bands will, in most cases, be sufficient.

A third reason for unreliable results at low frequencies is related to the excitation source, i.e., the venue's PA system. In general, PA systems are comprised of two different loudspeakers: subwoofers and mid/high-range speakers. The subwoofer placement in relation to the main speaker will vary from venue to venue, and it will depend on how the system is set up. In Figure 6.1a we see a typical example where the subwoofers are placed on the floor in a stereo configuration and with main speakers hanging from the ceiling. Another typical example is shown in Figure 6.1b. In this case, we see the subwoofers placed on the floor in a mono configuration. Common for both examples is that the subwoofer is placed at some distance from the main speakers. As a result, you will have two sender positions even though you play the sweep through one channel of the stereo PA system. In addition, when the subwoofers are set up in a mono configuration, you will only have one sender position at very low frequencies, even though the sweep is played via both channels of the PA system.

Furthermore, the crossover frequency between the subwoofer and main speakers is typically at 80-100 Hz. Let us take venue #2 (Figure 6.1a) as an example. This venue is fitted with JBL VRX932LAP main speakers and JBL VRX918S subwoofers. According to the manufacturer, the crossover frequency is 80 Hz with a 24 dB/octave slope [48]. Consequently, when recording an ESS played through this PA system, you will measure sound from two separate sources around 80 Hz, even though only one PA channel is active. It remains unclear to which degree this will affect the results.

(a) Venue #2: Kultursenteret ISAK Amfisalen (b) Venue #6: Studentersamfundet Storsalen

Figure 6.1: Photos taken during measurements of venue #2 and #6.

Another observation from the results in Section 5.1 is that the reverberation time gained from recordings of ESS played via a PA system is generally shorter than the one obtained from standardised measurements. In Section 4.1.2, the author commented on how the excitation source's directivity may influence the measurement results. As explained, the high directivity of the PA system at high frequencies may cause a lower reverberation time due to the initial peak in the impulse response. This might be why $e > 0$ s above 250 Hz in Figure 5.1.

Furthermore, this work is limited by the non-consistent choice of excitation signal. As discussed in Section 4.1, ESS is considered to be a preferable excitation signal when measuring reverberation time. In this study, both pink noise and impulse sources were used as excitation signal in the standardised measurements. In hindsight, all measurements should have been done using the same exponential sine sweep, as this would eliminate one uncertainty factor when comparing the two methods. On the other hand, it is common among acousticians to use pink noise and impulse sources when measuring reverberation time, so you could argue that the methodology used in this study reflects “real-life” situations.

6.2 Analysis of Kulturrom's database

6.2.1 Sound level analysis

This part of the thesis aimed to expand on the results of a previous study by Støfringsdal in 2018 [3]. Key results from Støfringsdal's study have been explored with the updated database, and correlation analysis between sound levels and information about venues from the survey sent out in 2018.

In 2018, Støfringsdal's filtered data set consisted of only 170 concerts, while the present study consists of 621 concerts. Results in Section 5.2 strengthens the findings by Støfringsdal. In Figure

5.3, we find similar results as Støfringsdal. A substantial part of the dataset have max $L_{A,Eq,15\text{ min}}$ level close to the warning level of 102 dB. As Støfringsdal indicated, this might indicate that sound engineers aim for the warning level when mixing concerts. As seen in Figure 6.2, each venue is fitted with a touch monitor that displays current sound levels at front-of-house, so the sound engineer will always know the sound level, and therefore may choose to use the objective measurements as a tool when aiming for the warning level. Another possible explanation is that this is a desirable sound level at concerts for amplified music.

Figure 6.2: Venue #3: Nidelven Bar & Scene at front-of-house. Here we see some of the sound logging equipment subsidised by Kulturrom.

Moreover, the expected differences between key parameters in Table 5.1 further support the results by Støfringsdal. As mentioned, it is expected to experience maximum C-weighted levels of 122 ± 4 dB when attending concerts with a warning level of $L_{A,Eq,15\text{ min}}$ 102 dB. The maximum C-weighted level is highly relevant for sound insulation purposes, as the dominant part of the energy is at low frequencies. This is backed by the energy spectrum in Figure 5.4, which shows a maximum average sound level around 50 Hz for pop/rock concerts.

As previously mentioned in Section 3.2 and shown in Figure 3.4, the calibration sensitivity differs quite a lot in the different measurements, hence why only measurements with calibration sensitivity greater than 2 and less than 10 mV/Pa were included. In the analysis, the author contemplated whether all measurements should be adjusted to a similar calibration sensitivity. This is in theory possible, as sensitivity in a linear unit of mV/pa can be expressed logarithmically in decibels [49]:

$$Sensitivity_{\text{ dBV}} = 20log_{10}\left(\frac{Sensitivity_{\text{ mV/Pa}}}{Output_{\text{ REF}}}\right) \tag{6.1}$$

where $Output_{REF}$ is the 1000 mV/pa reference output ratio. This relationship implies a 6 dB increase in level for every doubling of calibration sensitivity. However, due to the natural variance of calibration sensitivity for different microphones, a decision was made not to adjust the sound levels to a reference calibration sensitivity.

6.2.2 Correlation analysis

In the correlation analysis, results indicate a significant correlation between the mean Max $L_{A,Eq,15\text{ min}}$ level of each venue and room volume, room height, definition (D_{50}) and bass ratio (BR).

It is interesting to note that increasing room geometry leads to lower sound levels. There may be several explanations for this. In small venues, the sound exposure in the audience area is heavily affected by the sound from the stage, i.e., the *natural* sound level of acoustic drums and guitar amplifiers. This means that the sound engineers ability to reduce the sound level at small venues is limited by the artist's ability to play softer. In pop/rock concerts, this is often difficult to achieve. In the author's personal experience as a live sound engineer, it may be difficult to achieve a *punchy* and *warm* sound when mixing pop/rock shows in small venues where the artist or band plays loud on stage while trying to reduce the sound level in the audience area. Hence, the sound engineer will often feel a need to increase the sound level. In contrast, in multi-purpose venues such as a bar, the audience's noise level may sometimes be so loud that if the artist plays too soft, the sound engineer may need to increase the sound level to drown out the noise of the audience.

Another possible explanation is that the direct sound of the PA system is high compared to the sound level in the diffuse sound field, as both the audience and sound engineer may be very close to the PA system in small venues. In larger venues, a large part of the audience may be beyond the *critical distance* from the loudspeakers and therefore experience the diffuse field sound level.

Furthermore, in small venues, the sound emitted by the PA system may become very loud on stage. As a result, the musicians may have no other choice but to turn up their monitoring. If they are not using in-ear monitors, the sound level from the monitors may get so loud that the sound from the monitors blends with the PA system in the audience area. In such cases, the sound engineer may feel obligated to increase the sound level of the PA system. Hence, you end up in an evil spiral where the sound level is too high both in the audience area and on stage. In the author's experience, this is a recurrent problem at small venues where the PA system is very close to the musicians on stage.

$\mathbf{D_{50}}$, or definition, was investigated because the lyrical content and rhythmic information are essential in the investigated genres. As Adelman-Larsen et al. pointed out [26], the intelligibility/clarity parameter with the shortest integration time is the most relevant in genres of popular music, and therefore, D_{50} was chosen over C_{80}. In fact, when considering that pop/rock often contains complex and rapid rhythmical patterns and that sound travels 17 m in 50 ms, one could argue that even shorter time spans should be investigated in the future.

An interesting point to note here is that increasing values of D_{50} gives increasing sound levels. In other words, if the early energy (0-50 ms) $\approx$ the total energy (0-∞ ms), the sound level will be higher than if the early energy is low compared to the total energy. This may not be surprising given the fact that a low D_{50} value indicates that most of the energy is from the reverberant sound field, and vice versa. As discussed earlier, if the direct sound of the PA system is loud compared to the reverberant sound field in the audience area, you may experience higher sound levels.

Another factor may be that the sound engineer feels that it is necessary to reduce the sound level at venues with a low D_{50} value to avoid a *muddy* mix. In venues where most of the energy is within 50 ms, the sound level can perhaps be increased without losing clarity.

BR, or bass ratio, was used as a way of quantifying whether the reverberation time is frequency independent or not. It is commonly agreed in literature that a flat frequency response is sought after in venues for amplified music. Therefore, it is interesting that higher bass ratios, i.e., when the reverberation time is high at low frequencies (63-250 Hz) compared to high frequencies (500-2000 Hz), lead to lower sound levels. This is surprising given the fact that it is often desirable to have a bass ratio $\approx$ 1 or less in venues for amplified music.

In addition, it is somewhat surprising that a significant correlation was found for BR, but not any of the other parameters related to the decay curve of the impulse response. However, in Table 5.2 we saw that the correlation between the mean max $L_{A,Eq,15\text{ min}}$ level and $T_{20,B}$ (63-125 Hz) had a p-value of 0.069 which is not far from being considered significant. Here we see a similar trend as BR; the sound level increases with reverberation time. Given this, along with the fact that significant correlation was found between the mean max $L_{A,Eq,15\text{ min}}$ level and bass ratio, it could mean that the reverberation time at low frequencies plays an important role in the sound level exposure at concerts.

Moreover, we saw a strong significant correlation between the volume of a venue and $T_{20,W}$. This is as expected, as previous studies have come to the same conclusion, and the famous reverberation time formula by Sabine is a function of volume. Hovewer, it was interesting to note that the slope of the curve found in this study was not as steep as the curve proposed by Adelman et al. [26].

Despite the success demonstrated in the correlation analysis, there are several limitations associated with this study which we will discuss below.

All results regarding room acoustic properties (T, EDT, D_{50}, and BR) are derived from the room impulse responses gained from FFT-based deconvolution of recordings of ESS in one receiver position played through the PA system. The uncertainties in these measurements have been discussed for reverberation time in Section 6.1, but the uncertainty of EDT and D_{50} have not been quantified. It remains unclear if this measurement method can be used to derive these parameters with low uncertainty. Earlier, we looked at the decay curve in a typical room impulse response and saw an initial drop in the level that likely is caused by the loudspeaker's directivity (Figure 4.2 and 4.3). EDT is derived from the 0 to -10 dB of the decay curve. Hence, the calculated EDT may be too low in mid/high frequencies, and in Table 5.3 we observed that EDT $\leq T_{20,W}$ for all venues. A similar trend may be observed with D_{50}, as the energy from 0-50 ms may be heavily influenced by the direct sound of the loudspeakers. However, in a previous study [50], no systematic difference was found between measurements of EDT in the audience using an omnidirectional source or a PA system. In addition, Adelman-Larsen et al. found no significant difference between measurements of T_{30}, EDT, and D_{50} in the audience area when using an omnidirectional source or a PA system. That being said, there may be receiver positions for which there will be a difference between the two source types.

Both $T_{20,B}$ and BR are based on low-frequency reverberation time down to the 63 Hz octave band. As previously seen, the uncertainty in this frequency range is high compared to the uncertainty at high frequencies. Therefore, these results may not be reliable. Another factor that may especially influence the bass ratio is the fact that room impulse responses were measured in empty rooms, while all data from concerts are in occupied rooms. Many venues for amplified music do not have any chairs in the audience area. As mentioned, a study by Adelman-Larsen et al. [26] showed that the absorption coefficients of a standing audience are five to six times higher at mid/high frequencies than at low frequencies. Hence, the bass ratio will increase when there is a standing audience in the room.

Another limitation is the sample size. As stated, the total amount of venues in the filtered data set is 50. Even though 28 participating venues have recorded the ESS, only 14 of these are included in the filtered data set due to the criteria chosen in Table 3.4. Moreover, not all of the 50 included venues answered the survey from 2018.

6.3 Further work

Several interesting aspects related to Kulturrom's database may be further explored. Firstly, an effort to categorise all events in genres should be made. It is a shame that 1755 measurements do not have genre specification at the time of this study. If this is done, it is possible to analyse the database with respect to genres further. For example, there may be different acoustic needs for a jazz venue than a rock venue, even though both can be classified as amplified music. In addition, an effort should be made to get recordings of ESS from every participating venue to increase the sample size in future research.

Secondly, it would be interesting to follow a professional artist or band with their own sound engineer and production on tour. Then, it would be possible to get objective comparisons between different venues. In addition, it would be possible to interview both the sound engineer and the musicians after each show to get their opinion on the venue's acoustics or the subjective experience of sound level. Since acoustic memory is short, such interviews should be done in a short time period after each concert.

Thirdly, there is a great variety of different sound system designs throughout the participating venues. It remains unclear how this affects the room impulse response measured when measured through the PA system. In addition, it could be interesting to explore how different PA systems affect properties like stage conditions, spectral content, and sound levels.

Other interesting aspects may include a further investigation of the spectral content in the database. The spectral content, along with the measured sound levels, may provide a foundation when designing sound insulation in new venues. Therefore, further studies could include an analysis of the construction surrounding typical pop/rock venues and what is needed to fulfil requirements set in standards.

Chapter 7

Conclusion

By analysing sound level data from 621 concerts in 50 venues, and room impulse responses for 28 venues, the knowledge gap on sound levels in Norwegian concert venues for amplified music has been decreased. In recent years, the focus on sound levels at concerts for amplified music has escalated. In 2017, Kulturrom initiated a project to monitor sound levels at Norwegian concert venues. As of this study, this project has 107 participating venues and more than 4300 measurements of concerts and events.

In a survey from 2018, participating venues received an exponential sine sweep which 28 venues played through the PA system and recorded in one receiver position using the equipment subsidised by Kulturrom. Using FFT-based deconvolution, room impulse responses were created in MATLAB of these recordings. The room impulse responses were analysed in both ODEON and EASERA, giving conflicting results at low frequencies. To assess the uncertainty of the reverberation time gained from these impulse responses, reverberation time was measured at six venues using ISO 3382-1. Results reveal a high uncertainty below the 250 Hz octave band, but from the 250 Hz octave band and above, the mean error was below 0.1-0.2 s.

In the course of the analysis of the sound level data, it was discovered that many concerts lie close to the warning level of $L_{A,Eq,15\text{ min}}$ 102 dB. 14 % of the concerts had max $L_{A,Eq,15\text{ min}} > 102$ dB. Expected $L_{CF,max}$ values of concerts at the warning level is 122 dB. Furthermore, a review of the spectral content in pop/rock-, jazz- and singer-songwriter/acoustic concerts show that a substantial part of the energy is below 100 Hz.

Moreover, significant correlations ($p < 0.05$) were found between the mean max $L_{A,Eq,15\text{ min}}$ level in each venue and room volume, room height, EDT (63-2000 Hz), D_{50} (63-2000 Hz), and BR (ratio of T_{20} (63-250 Hz) and T_{20} (500-2000 Hz)).

In conclusion, the method of recording an ESS in one receiver position from the PA system can be used for quick analysis where high accuracy at low frequencies is not crucial. Furthermore, the analysis of Kulturrom's database reveals a need to increase the focus on sound level limits at Norwegian concerts for amplified music. The acoustic design may influence the sound exposure of attendees and employees at concert venues.

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Appendix A

Included venues and geometry data

Table A.1: A complete list of all included venues in the filtered data set, along with their respective room height, volume and audience capacity. This is gathered from the 2018 survey, `www.scenerommet.no`, and the venue's websites. An attempt to contact every venue with missing information was done, and answers from those attempts are included.

Venue	**Room height** [m]	**Volume** [m^3]	**Audience capacity**
Askim Kulturhus	8	-	514
Arendal Kulturhus - Lille Torungen	13	3250	1241
BIKS Fensal	6	1165	200
Bluebox	7	-	700
Blå Grotte	10	4800	451
Bølgen Kulturhus - Sanden	4	-	-
Bølgen Kulturhus - Storsalen	7	-	506
Cosmopolite	8	4000	700
Dokkhuset Scene	4	760	450
Elverum Kulturhus	5	3100	335
Energimølla	-	-	-
Folken	6	1848	650
Foynhagen	-	-	-
Gamle Total Scene & Bar	4	529	300
Gregers	4	-	400
Hulen	3	312	320
Ibsenhuset - Dovregubbens hall	7	7000	800
Ibsenhuset - Peer Gynt-salen	6	2112	270
Jernvaren	3	360	200
John dee	-	-	400
KICK Nattklubb & Scene	6	2592	700
Kolben Kulturhus - sal 1	15	7020	419
Kulturscenen Cafe Stift	-	-	-
Kvarteret Teglverket	4	445	400
Ludo Bar & Scene	2	172	250
Maskinverkstedet	4	960	400
Nasjonal Jazzscene	4	672	300
Nidelven Bar & Scene	2	320	200
Ofelas Arena	5	1764	350
Parkteatret	5	1050	500
Prelaten Kro og Scene	3	264	200

Table A.1 continued from previous page

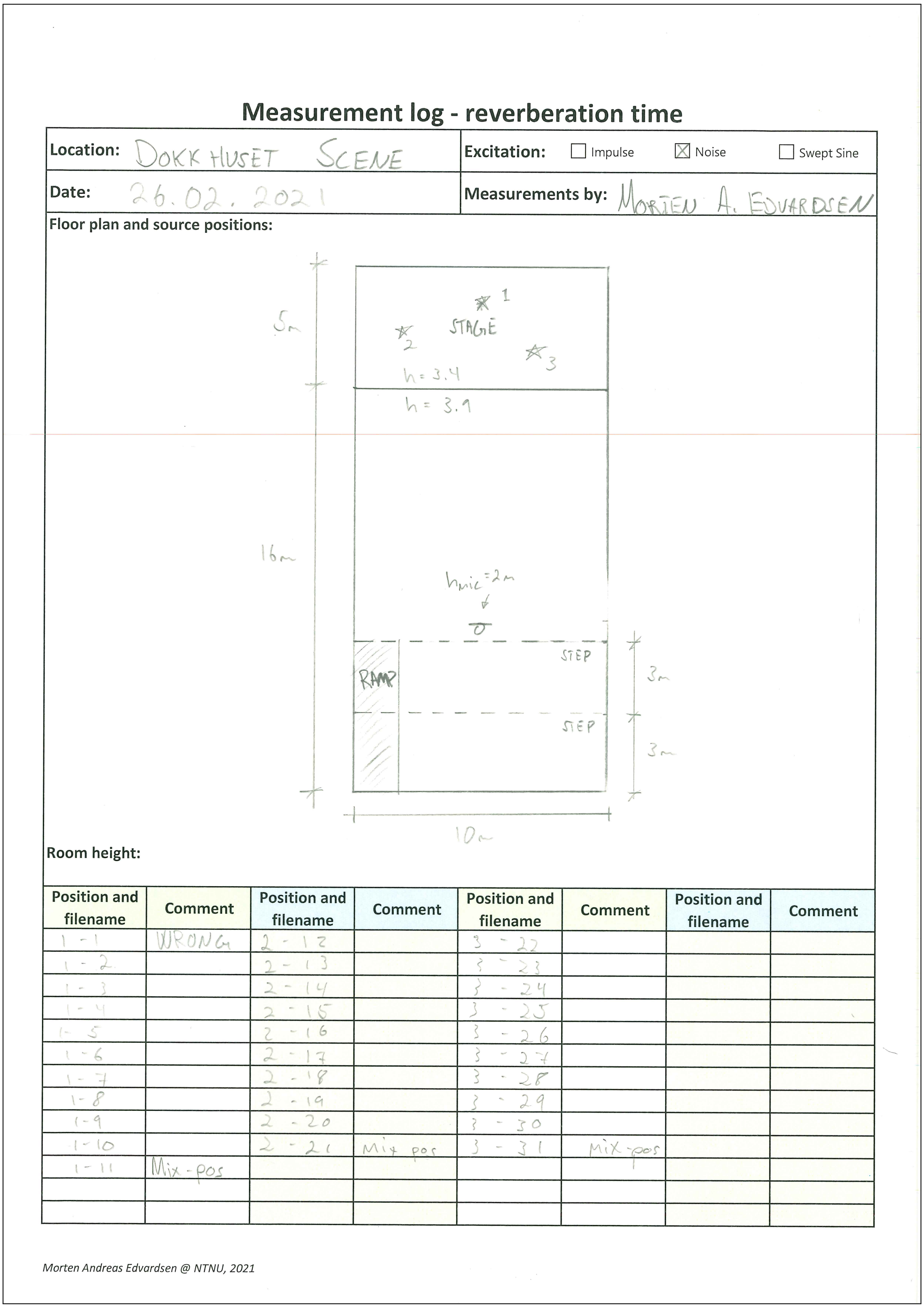
Riksscenen - Hovedsalen	10	3780	666
Rockeklubben i Porsgrunn	2	255	160
Sandnes Kulturhus - Storsalen	12	9120	666
Sentrum Scene	7	-	1750
Sola Kulturhus	14	7840	450
St. Croix-huset	-	-	100
Stormen Konserthus - Store sal	18	11340	940
Studenthuset City Scene	4	1294	350
Studenthuset Gjøvik	-	-	-
Støperiet Scene	6	2520	800
Uhørt	5	800	180
Union Scene	-	-	1200
USF - Røkeriet	-	-	1300
USF - Sardinen	-	-	420
USF - Studio	-	-	300
Vadsø Jazzklubb/Kooperativet	-	-	-
Vulkan Arena	6	1461	600
ØSTRE	5	440	200
Østsia	3	-	375

Appendix B

Measurement logs

In the current appendix, measurements logs for each venue will be presented.

B.1 Dokkhuset Scene



Measurement log - reverberation time

Location:	DOKKHUSET SCENE	**Excitation:**	☐ Impulse ☒ Noise ☐ Swept Sine
Date:	26.02.2021	**Measurements by:**	MORTEN A. EDVARDSEN

Floor plan and source positions:

Room height:

Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1-1	WRONG	2-12		3-22			
1-2		2-13		3-23			
1-3		2-14		3-24			
1-4		2-15		3-25			
1-5		2-16		3-26			
1-6		2-17		3-27			
1-7		2-18		3-28			
1-8		2-19		3-29			
1-9		2-20		3-30			
1-10		2-21	Mix pos	3-31	Mix-pos		
1-11	Mix-pos						

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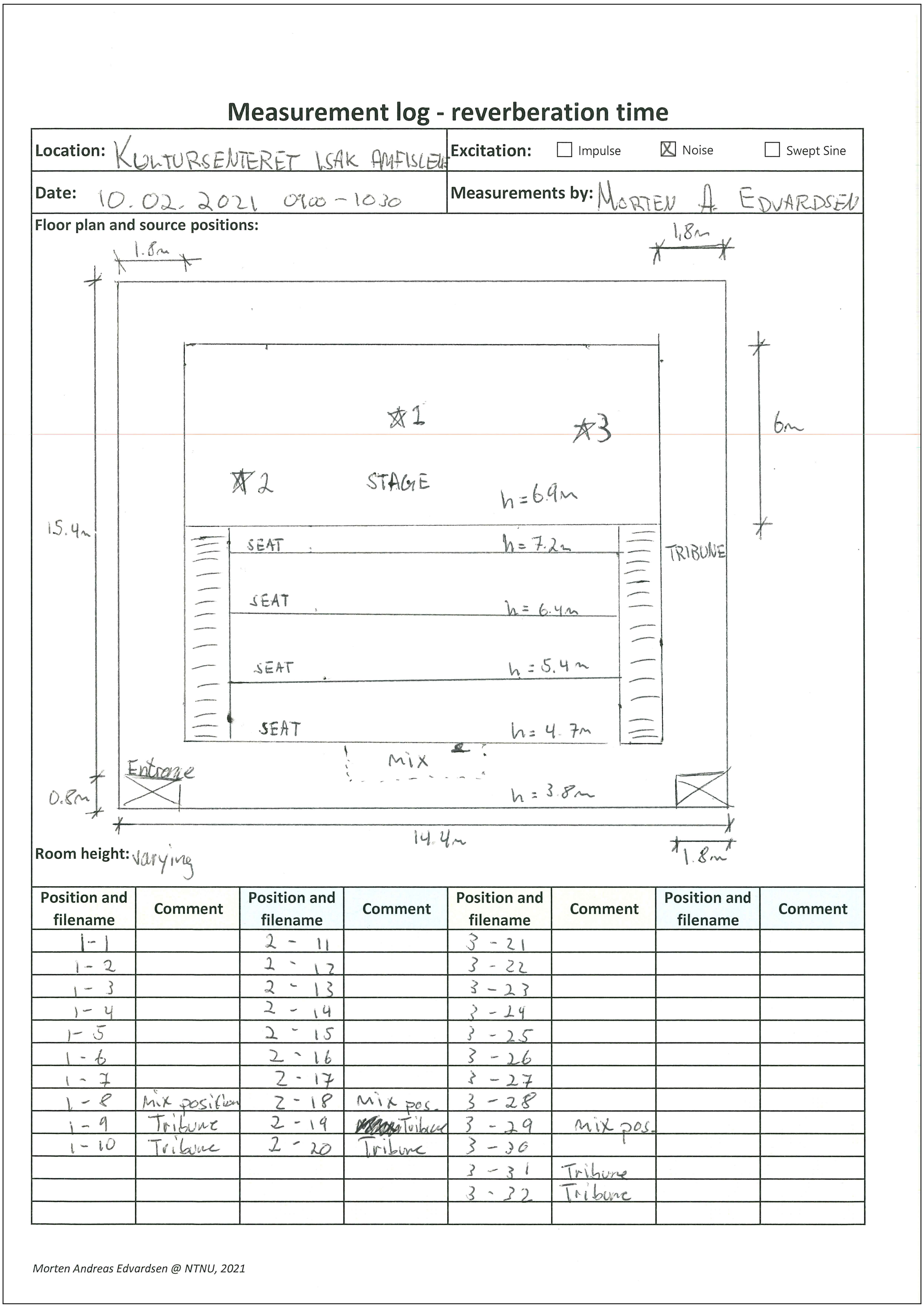
Table B.1: Measurements of T_{20} from Dokkhuset Scene.

T_{20} [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
N/A	1.26	1.16	1.34	1.11	1.08	1.30	1.00	0.87	1.02	0.70	0.80	0.83	0.76	0.70	0.76	0.69	0.83	0.73	0.67	0.66	0.60	0.50	0.46
N/A	1.05	0.90	1.45	1.47	1.21	0.84	0.88	1.00	0.76	1.06	0.85	0.86	0.95	0.90	0.74	0.88	0.86	0.76	0.68	0.63	0.59	0.50	0.49
N/A	1.29	2.02	1.93	1.22	1.07	1.14	0.92	0.81	0.72	0.69	0.86	0.83	0.86	0.74	0.77	0.74	0.79	0.80	0.69	0.61	0.58	0.54	0.44
0.85	1.93	1.38	1.96	1.21	1.52	0.91	1.07	1.25	0.67	0.85	0.74	0.89	0.79	0.89	0.77	0.75	0.72	0.83	0.75	0.70	0.60	0.52	0.47
N/A	0.94	1.18	1.34	0.98	1.17	1.38	0.88	0.81	0.75	0.74	0.94	0.86	0.89	1.01	0.85	0.78	0.76	0.88	0.72	0.62	0.61	0.54	0.50
2.27	N/A	2.12	1.28	1.27	1.15	1.17	1.04	1.18	0.84	0.89	1.10	0.95	0.70	0.85	0.83	0.78	0.70	0.78	0.67	0.64	0.59	0.49	0.46
N/A	1.04	1.18	1.22	2.02	1.51	0.95	0.94	0.93	0.74	0.86	0.79	0.75	0.78	0.83	0.74	0.77	0.77	0.81	0.64	0.61	0.56	0.51	1.12
N/A	1.46	1.27	1.15	1.26	1.21	0.70	0.88	0.77	0.73	0.71	0.61	0.72	0.76	0.85	0.78	0.80	0.82	0.80	0.70	0.67	0.58	0.50	0.46
N/A	1.38	1.80	1.40	1.11	1.23	0.99	1.11	0.84	0.74	0.73	0.77	0.63	0.80	0.89	0.80	0.75	0.77	0.71	0.68	0.65	0.57	0.54	0.40
N/A	1.17	1.11	1.19	1.17	1.19	1.18	1.00	0.66	0.72	0.74	0.64	0.75	0.68	0.75	0.77	0.86	0.80	0.74	0.70	0.64	0.63	0.52	0.50
N/A	1.73	1.03	1.21	1.02	1.32	0.89	1.20	0.81	0.85	0.75	0.84	0.84	0.78	0.80	0.99	0.91	0.79	0.75	0.66	0.59	0.54	0.50	0.48
N/A	0.67	1.12	1.22	1.35	1.49	0.92	1.09	0.68	0.74	0.74	0.72	0.76	0.83	0.83	0.85	0.80	0.80	0.74	0.73	0.65	0.59	0.51	0.44
N/A	1.41	2.09	0.83	1.05	0.90	0.96	0.99	0.87	0.85	0.67	0.83	0.68	0.73	0.75	0.90	0.86	0.83	0.75	0.74	0.60	0.55	0.54	0.44
N/A	0.53	0.95	0.54	0.12	1.27	1.15	1.64	0.86	1.05	0.88	0.70	0.88	0.76	0.90	0.90	0.90	0.80	0.78	0.70	0.69	0.60	0.57	0.47
3.47	2.28	1.24	1.02	1.43	1.11	1.08	1.10	0.68	0.70	0.80	0.89	0.91	0.76	0.68	0.70	0.75	0.81	0.82	0.70	0.60	0.53	0.51	0.42
N/A	1.08	0.84	1.48	0.95	1.22	0.96	1.08	0.82	0.70	0.85	0.89	0.76	0.78	0.84	0.88	0.82	0.72	0.76	0.65	0.66	0.59	0.50	0.45
N/A	1.27	0.96	1.13	1.37	1.05	1.10	1.03	0.89	0.86	0.82	0.67	0.73	0.84	0.79	0.83	0.78	0.80	0.78	0.75	0.65	0.58	0.49	0.49
1.57	1.29	1.06	1.14	1.85	1.04	1.38	0.93	0.91	0.71	0.71	0.79	0.94	0.77	0.68	0.75	0.81	0.80	0.77	0.70	0.73	0.64	0.52	0.48
N/A	1.24	0.94	1.00	1.05	1.03	0.78	0.97	0.98	0.82	0.85	0.85	0.91	0.84	0.87	0.81	0.81	0.85	0.74	0.74	0.64	0.67	0.55	0.48
N/A	1.32	1.61	1.41	2.37	1.67	0.98	1.04	0.89	0.87	0.98	0.72	0.67	0.87	0.84	0.76	0.76	0.76	0.73	0.68	0.66	0.58	0.54	0.50
N/A	1.18	1.04	0.88	1.13	0.82	1.18	0.53	0.88	0.80	0.72	0.75	0.64	0.79	0.81	0.77	0.84	0.79	0.91	0.71	0.61	0.54	0.52	0.49
N/A	1.09	0.80	1.63	1.41	1.23	1.17	0.92	0.85	0.81	0.81	0.66	0.85	0.88	0.85	0.82	0.73	0.82	0.73	0.73	0.60	0.60	0.50	0.47
N/A	1.38	1.17	1.17	1.06	0.94	0.82	0.81	1.05	0.88	0.75	0.71	0.80	0.78	0.80	0.76	0.81	0.83	0.74	0.72	0.75	0.61	0.51	0.48
N/A	1.66	1.35	0.85	0.89	1.21	1.00	1.06	0.70	0.73	0.65	0.82	0.78	0.83	0.77	0.84	0.83	0.77	0.86	0.71	0.66	0.62	0.53	0.46
N/A	1.97	1.83	1.44	1.01	1.35	0.96	1.23	0.94	0.66	0.88	0.77	0.85	0.82	0.73	0.90	0.77	0.73	0.70	0.73	0.59	0.59	0.48	0.45
N/A	1.53	0.66	1.05	0.81	0.99	2.10	0.99	0.84	0.97	0.88	0.92	0.79	0.93	0.85	0.83	0.75	0.79	0.72	0.79	0.69	0.54	0.50	0.44
0.93	2.19	1.55	1.11	0.90	1.08	1.03	1.04	0.91	0.90	0.74	0.98	0.87	0.80	0.94	0.76	0.81	0.82	0.67	0.73	0.65	0.58	0.53	0.83
0.98	1.28	1.22	0.71	1.42	1.14	0.97	1.18	0.61	0.60	0.79	0.81	0.74	0.80	0.95	0.83	0.77	0.78	0.79	0.76	0.62	0.60	0.51	0.47
0.89	0.87	1.45	0.98	1.05	0.98	0.84	1.00	1.06	0.84	0.71	1.05	1.22	0.83	0.86	0.84	0.77	0.79	0.78	0.70	0.68	0.63	0.52	0.44
N/A	1.26	1.83	1.14	1.17	0.83	1.03	1.11	1.11	0.79	0.86	0.81	0.92	0.76	0.71	0.85	0.75	0.78	0.78	0.68	0.74	0.62	0.54	0.47

B.2 Kultursenteret ISAK - Amfisalen



Measurement log - reverberation time

Location: KULTURSENTERET ISAK AMFISLEN	**Excitation:** ☐ Impulse ☒ Noise ☐ Swept Sine
Date: 10.02.2021 0900 - 1030	**Measurements by:** MORTEN A. EDVARDSEN

Floor plan and source positions:

Room height: varying

Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1-1		2-11		3-21			
1-2		2-12		3-22			
1-3		2-13		3-23			
1-4		2-14		3-24			
1-5		2-15		3-25			
1-6		2-16		3-26			
1-7		2-17		3-27			
1-8	Mix position	2-18	Mix pos.	3-28			
1-9	Tribune	2-19	[illegible] Tribune	3-29	Mix pos.		
1-10	Tribune	2-20	Tribune	3-30			
				3-31	Tribune		
				3-32	Tribune		

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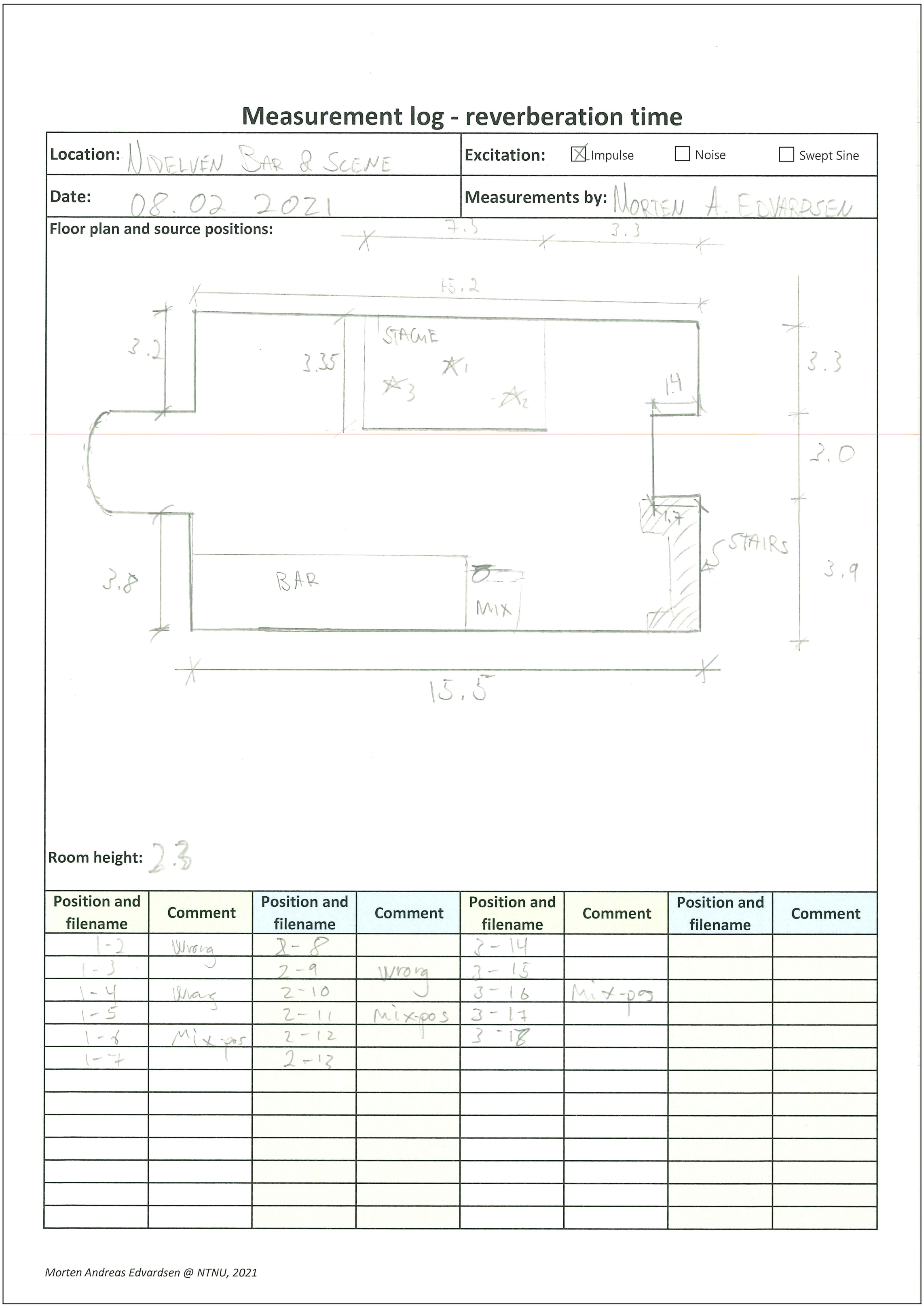
Table B.2: Measurements of T_{20} from Kultursenteret ISAK - Amfisalen

T20 [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
N/A	1.16	2.00	3.64	1.06	0.81	1.15	1.14	0.84	0.69	0.67	0.78	0.66	0.72	0.70	0.71	0.74	0.71	0.61	0.53	0.51	0.44	0.40	0.36
N/A	1.12	1.13	2.08	1.26	1.58	1.18	0.72	0.81	0.95	0.75	0.76	0.79	0.64	0.82	0.75	0.75	0.65	0.64	0.54	0.56	0.51	0.47	0.42
N/A	1.28	1.07	3.11	1.73	1.24	1.04	0.71	0.79	0.77	0.74	0.79	0.79	0.82	0.73	0.64	0.70	0.63	0.60	0.60	0.54	0.50	0.44	0.44
N/A	0.93	1.50	1.24	1.32	0.90	1.20	1.04	1.00	0.72	0.75	0.68	0.78	0.91	0.78	0.67	0.73	0.71	0.60	0.59	0.58	0.49	0.39	0.35
N/A	1.38	1.12	1.18	1.50	1.95	1.45	0.89	0.81	0.96	0.89	0.78	0.81	0.78	0.74	0.84	0.71	0.61	0.64	0.57	0.54	0.51	0.49	0.44
N/A	1.51	1.62	0.87	1.53	0.86	0.94	0.77	1.27	0.76	1.06	0.73	0.74	0.82	0.80	0.86	0.75	0.63	0.63	0.62	0.56	0.47	0.49	0.48
N/A	1.30	1.93	1.22	0.89	1.06	1.20	0.89	0.92	0.84	1.08	0.79	0.77	0.78	0.83	0.73	0.67	0.63	0.60	0.59	0.52	0.50	0.46	0.46
N/A	5.41	1.59	2.37	1.26	1.37	1.74	1.10	0.89	0.94	0.84	0.97	0.66	0.78	0.75	0.83	0.80	0.67	0.67	0.59	0.53	0.50	0.45	0.37
N/A	1.12	1.83	1.53	0.97	1.15	0.78	0.69	0.92	0.79	0.75	0.82	0.85	0.80	0.90	0.71	0.68	0.64	0.63	0.57	0.53	0.46	0.43	0.40
N/A	1.47	2.35	1.85	1.83	1.53	1.70	0.65	1.04	0.93	0.91	1.02	0.84	0.82	0.72	0.72	0.75	0.71	0.61	0.60	0.58	0.49	0.45	0.44
N/A	1.53	0.91	1.78	1.13	1.22	1.06	0.98	0.67	0.77	0.95	0.77	0.78	0.81	0.82	0.76	0.72	0.71	0.57	0.51	0.48	0.50	0.38	0.41
N/A	0.82	1.05	1.26	1.07	1.07	1.07	0.98	0.74	0.89	0.91	0.87	0.73	0.83	0.83	0.75	0.69	0.67	0.59	0.51	0.48	0.43	0.41	0.41
N/A	0.78	1.51	1.79	1.81	1.61	1.25	1.10	0.96	0.90	0.85	0.82	0.75	0.73	0.80	0.70	0.66	0.67	0.68	0.56	0.54	0.50	0.44	0.42
N/A	0.56	1.30	0.90	0.88	1.82	0.81	0.90	0.88	0.89	0.90	0.94	0.69	0.82	0.81	0.81	0.74	0.62	0.61	0.60	0.48	0.51	0.44	0.43
N/A	1.54	2.49	1.21	1.28	1.00	0.85	0.96	0.85	0.76	0.80	0.74	0.85	0.87	0.88	0.69	0.73	0.68	0.67	0.60	0.50	0.48	0.43	0.39
N/A	0.93	2.90	3.00	1.33	0.99	1.04	0.92	0.83	0.91	0.98	0.71	0.70	0.81	0.84	0.86	0.76	0.64	0.64	0.52	0.50	0.45	0.42	0.37
N/A	0.75	1.40	1.94	1.01	1.14	1.09	1.65	0.76	0.88	0.78	0.48	0.77	0.84	0.82	0.67	0.70	0.71	0.61	0.53	0.49	0.45	0.40	0.38
N/A	0.59	1.79	1.89	1.37	1.15	1.22	1.03	0.77	0.94	0.58	0.64	0.84	1.01	0.92	0.67	0.66	0.60	0.61	0.52	0.48	0.47	0.45	0.35
N/A	1.21	1.89	1.54	1.40	1.18	1.23	1.20	0.80	0.71	0.86	0.77	0.87	0.93	1.03	0.85	0.75	0.72	0.68	0.59	0.56	0.45	0.45	0.44
N/A	1.06	1.57	1.65	1.19	1.26	1.05	0.87	0.79	0.93	1.12	0.87	0.86	0.82	0.67	0.79	0.72	0.63	0.62	0.58	0.49	0.53	0.43	0.40
N/A	1.10	2.20	2.64	1.63	1.23	1.26	0.82	0.96	1.00	1.00	0.67	0.71	0.71	0.77	0.75	0.71	0.66	0.60	0.57	0.51	0.50	0.42	0.44
N/A	0.64	1.52	1.03	1.54	1.63	1.43	0.96	0.86	0.77	0.97	0.69	0.99	0.78	0.79	0.82	0.81	0.67	0.62	0.57	0.51	0.50	0.46	0.44
N/A	0.93	1.71	1.66	1.38	1.17	1.00	1.08	0.82	0.80	0.88	0.83	1.23	0.69	0.80	0.70	0.67	0.62	0.65	0.58	0.52	0.49	0.43	0.39
N/A	0.96	1.34	1.11	1.70	1.23	1.19	1.00	1.17	0.79	0.82	0.83	0.90	0.76	0.82	0.80	0.83	0.63	0.68	0.58	0.54	0.48	0.44	0.38
N/A	3.85	0.66	1.48	1.01	1.26	1.12	0.68	0.84	0.85	1.07	0.88	0.74	0.79	0.90	0.78	0.78	0.68	0.66	0.51	0.51	0.52	0.43	0.39
N/A	1.12	1.81	1.73	1.48	1.13	0.89	0.79	0.87	0.75	0.73	0.69	0.81	0.72	0.82	0.77	0.77	0.67	0.57	0.61	0.61	0.46	0.46	0.42
N/A	N/A	1.49	1.44	1.14	1.11	1.47	0.74	0.78	0.84	0.83	0.78	0.73	0.83	0.85	0.76	0.73	0.61	0.62	0.54	0.51	0.47	0.44	0.39
N/A	1.18	1.50	1.33	1.57	1.12	1.58	1.08	1.21	0.78	0.52	0.78	0.71	0.75	0.71	0.82	0.69	0.58	0.62	0.51	0.47	0.48	0.44	0.39
N/A	1.53	1.70	1.05	1.18	1.45	1.26	0.96	0.95	0.91	0.96	0.80	0.78	0.78	0.82	0.78	0.67	0.66	0.61	0.53	0.48	0.51	0.43	0.42
N/A	5.77	0.93	1.22	1.79	1.37	1.08	1.10	1.09	0.92	0.87	0.76	0.81	0.78	0.69	0.81	0.74	0.65	0.62	0.55	0.51	0.44	0.43	0.39
N/A	1.46	2.40	1.67	1.42	1.37	1.93	0.96	0.95	1.06	0.90	0.72	0.74	0.71	0.93	0.69	0.65	0.68	0.61	0.48	0.53	0.48	0.45	0.42
N/A	1.59	1.58	1.35	1.27	1.28	1.24	0.83	0.91	0.85	1.19	0.79	0.90	0.76	0.81	0.72	0.80	0.57	0.58	0.52	0.47	0.49	0.46	0.40

B.3 Nidelven Bar & Scene



Measurement log - reverberation time

Location: Nidelven Bar & Scene	**Excitation:** ☒ Impulse ☐ Noise ☐ Swept Sine
Date: 08.02 2021	**Measurements by:** Morten A. Edvardsen

Floor plan and source positions:

Room height: 2.3

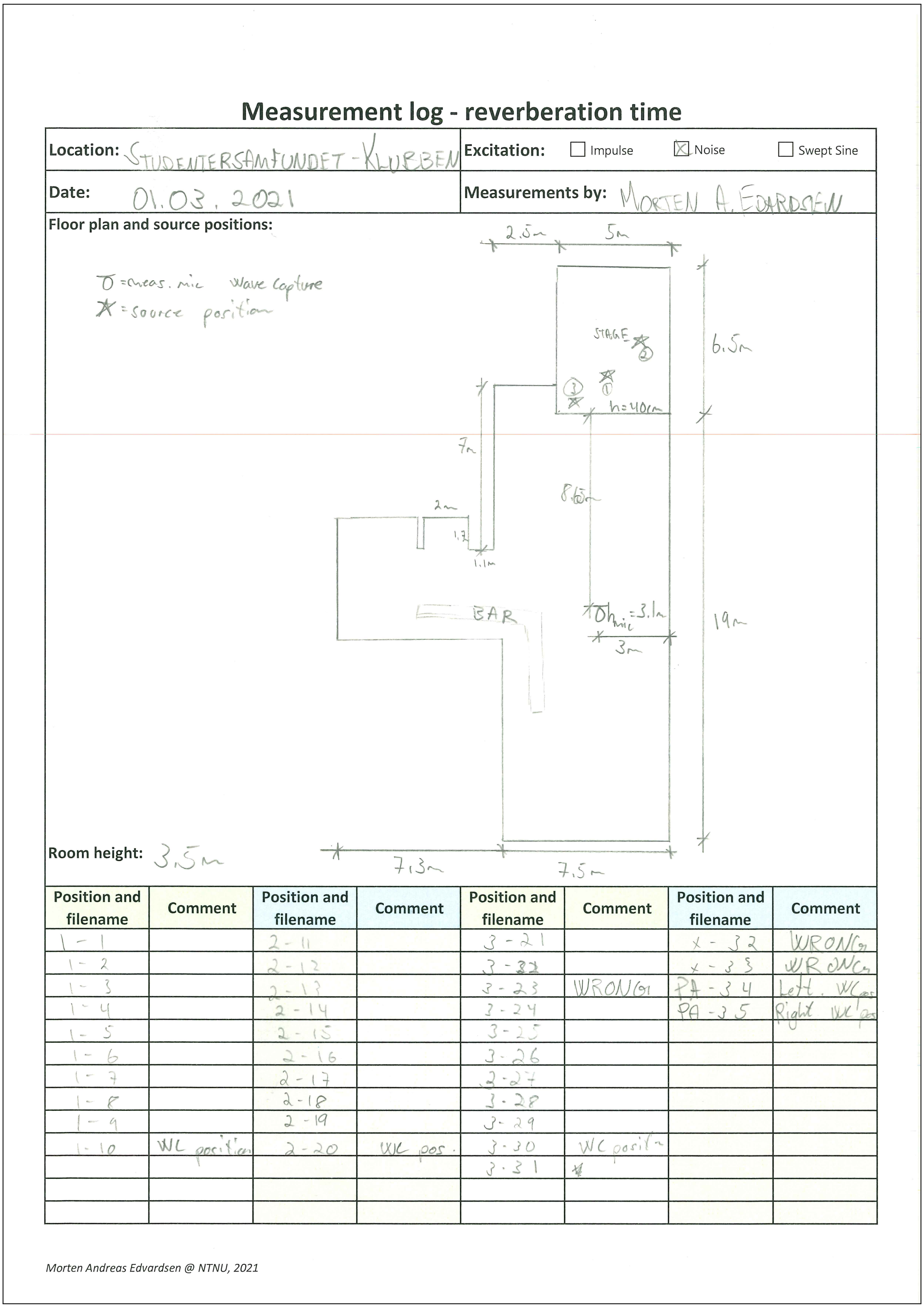
Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1-2	Wrong	2-8		3-14			
1-3		2-9	Wrong	3-15			
1-4	Wrong	2-10		3-16	Mix-pos		
1-5		2-11	Mix-pos	3-17			
1-6	Mix-pos	2-12		3-18			
1-7		2-13					

Morten Andreas Edvardsen @ NTNU, 2021

Table B.3: Measurements of T_{20} from Nidelven Bar & Scene

T20 [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
0.33	0.42	0.35	0.65	0.51	0.62	0.47	0.55	0.61	0.56	0.50	0.53	0.48	0.51	0.60	0.50	0.53	0.48	0.52	0.44	0.40	0.39	0.35	0.34
0.22	0.60	0.87	0.67	0.40	0.57	0.63	0.56	0.54	0.56	0.49	0.49	0.53	0.56	0.52	0.53	0.54	0.49	0.51	0.46	0.40	0.36	0.37	0.32
0.31	0.32	0.44	0.46	0.50	0.63	0.72	0.59	0.59	0.43	0.50	0.54	0.62	0.58	0.58	0.57	0.55	0.49	0.48	0.49	0.50	0.41	0.39	0.37
0.39	0.49	N/A	0.40	0.50	0.39	0.53	0.58	0.53	0.63	0.49	0.44	0.53	0.49	0.60	0.57	0.54	0.51	0.50	0.46	0.44	0.40	0.40	0.38
0.17	0.34	0.62	0.57	0.49	0.51	0.48	0.55	0.66	0.59	0.63	0.47	0.55	0.55	0.54	0.53	0.55	0.55	0.47	0.49	0.46	0.46	0.41	0.38
0.58	0.50	0.43	0.42	0.37	0.44	0.67	0.60	0.51	0.54	0.53	0.57	0.52	0.55	0.60	0.58	0.56	0.56	0.51	0.48	0.46	0.45	0.41	0.40
0.49	0.71	0.56	0.46	0.45	0.47	0.52	0.49	0.72	0.62	0.54	0.55	0.58	0.55	0.58	0.57	0.58	0.50	0.52	0.45	0.40	0.36	0.32	0.28
N/A	0.55	0.54	0.56	0.55	0.57	0.67	0.53	0.61	0.48	0.50	0.52	0.62	0.61	0.56	0.61	0.59	0.54	0.53	0.47	0.46	0.41	0.40	0.39
0.23	0.66	0.56	0.43	0.47	0.59	0.51	0.74	0.69	0.57	0.57	0.61	0.58	0.54	0.61	0.60	0.52	0.48	0.49	0.47	0.46	0.42	0.37	0.36
0.51	0.56	0.36	0.60	0.43	0.51	0.67	0.69	0.71	0.54	0.43	0.54	0.55	0.62	0.55	0.54	0.61	0.53	0.53	0.47	0.45	0.41	0.37	0.36
0.61	0.45	0.80	0.57	0.64	0.66	0.53	0.65	0.58	0.55	0.53	0.70	0.59	0.54	0.55	0.58	0.57	0.52	0.53	0.47	0.42	0.43	0.35	0.32
0.48	0.71	0.51	0.33	0.39	0.47	0.60	0.48	0.43	0.51	0.47	0.53	0.51	0.53	0.59	0.52	0.52	0.46	0.41	0.40	0.42	0.36	0.36	0.33
N/A	0.23	0.47	0.66	0.44	0.63	0.63	0.48	0.39	0.48	0.60	0.61	0.49	0.54	0.56	0.59	0.58	0.56	0.54	0.52	0.45	0.41	0.42	0.40
N/A	0.47	0.66	0.38	0.53	0.65	0.56	0.46	0.49	0.52	0.53	0.54	0.50	0.60	0.56	0.61	0.56	0.52	0.53	0.50	0.45	0.42	0.41	0.36
0.46	0.45	0.62	0.27	0.33	0.62	0.45	0.60	0.71	0.62	0.55	0.47	0.55	0.56	0.55	0.56	0.51	0.56	0.52	0.52	0.42	0.41	0.40	0.31

B.4 Studentersamfundet - Klubben



Measurement log - reverberation time

Location: Studentersamfundet - Klubben

Excitation: ☐ Impulse ☒ Noise ☐ Swept Sine

Date: 01.03.2021

Measurements by: Morten A. Edardsen

Floor plan and source positions:

○ =meas. mic Wave capture
☆ = source position

Room height: 3.5m

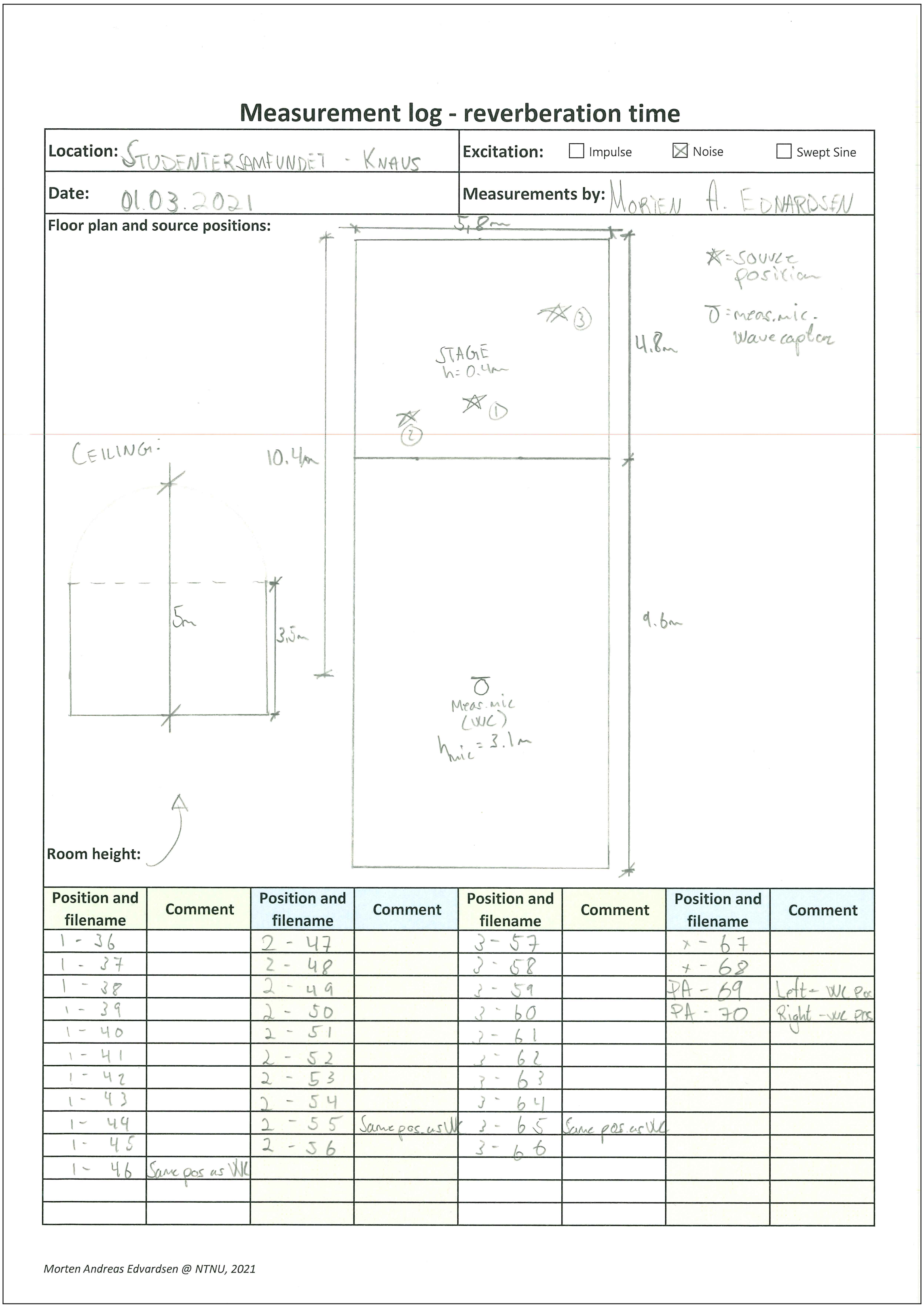
Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1 - 1		2 - 11		3 - 21		x - 32	WRONG
1 - 2		2 - 12		3 - 22		x - 33	WRONG
1 - 3		2 - 13		3 - 23	WRONG	PA - 34	Left. WC pos
1 - 4		2 - 14		3 - 24		PA - 35	Right WC pos
1 - 5		2 - 15		3 - 25			
1 - 6		2 - 16		3 - 26			
1 - 7		2 - 17		3 - 27			
1 - 8		2 - 18		3 - 28			
1 - 9		2 - 19		3 - 29			
1 - 10	WC position	2 - 20	WC pos.	3 - 30	WC position		
				3 - 31	☆		

Morten Andreas Edvardsen @ NTNU, 2021

Table B.4: Measurements of T_{20} from Studentersamfundet - Klubben

T20 [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
N/A	0.83	0.94	0.56	0.61	1.31	0.96	0.87	0.97	0.68	0.74	0.94	0.58	0.60	0.53	0.49	0.55	0.52	0.51	0.50	0.49	0.44	0.39	N/A
N/A	1.27	0.75	0.83	1.19	0.78	0.83	0.55	0.93	0.76	0.75	0.50	0.48	0.58	0.50	0.46	0.52	0.47	0.56	0.43	0.47	0.43	0.35	0.35
N/A	N/A	0.82	0.63	0.72	0.64	0.60	0.66	0.76	0.58	0.77	0.59	0.53	0.49	0.55	0.45	0.47	0.44	0.44	0.49	0.41	0.40	0.34	0.30
N/A	N/A	0.99	1.09	0.72	0.74	0.76	0.58	0.80	0.72	0.56	0.57	0.55	0.68	0.52	0.49	0.48	0.55	0.47	0.49	0.47	0.42	0.43	N/A
N/A	N/A	1.02	1.00	0.78	0.95	0.96	0.80	0.66	0.59	0.52	0.57	0.58	0.68	0.58	0.58	0.63	0.52	0.54	0.45	0.40	0.38	0.36	0.39
N/A	1.03	0.80	0.57	0.56	0.73	0.41	0.74	0.68	0.60	0.61	0.54	0.52	0.62	0.57	0.53	0.53	0.51	0.55	0.45	0.45	0.40	0.40	N/A
N/A	1.16	1.10	1.45	0.78	0.97	0.72	0.92	0.55	0.51	0.46	0.47	0.51	0.59	0.60	0.54	0.52	0.51	0.51	0.50	0.45	0.43	0.42	N/A
N/A	1.45	0.91	0.59	1.18	0.63	0.76	0.79	0.79	0.56	0.68	0.53	0.61	0.57	0.67	0.53	0.52	0.57	0.51	0.51	0.51	0.46	0.39	N/A
N/A	N/A	1.33	1.40	1.28	0.42	0.64	0.68	0.60	0.71	0.60	0.63	0.56	0.63	0.52	0.57	0.55	0.54	0.52	0.46	0.44	0.41	0.41	N/A
N/A	1.13	0.64	0.82	0.79	0.97	0.61	0.82	0.66	0.59	0.75	0.66	0.54	0.58	0.58	0.51	0.56	0.54	0.57	0.43	0.44	0.43	0.39	0.43
N/A	N/A	0.93	0.68	0.93	1.90	0.78	0.58	0.71	0.67	0.51	0.50	0.63	0.50	0.47	0.48	0.63	0.57	0.52	0.49	0.45	0.41	0.33	0.36
N/A	0.75	0.68	0.77	0.58	0.72	0.76	1.05	0.74	0.67	0.57	0.57	0.78	0.52	0.46	0.53	0.51	0.50	0.47	0.38	0.33	0.35	0.31	0.27
N/A	0.98	0.86	0.99	1.05	0.94	0.67	0.88	0.69	0.63	0.77	0.59	0.54	0.50	0.46	0.51	0.51	0.54	0.48	0.53	0.46	0.40	0.35	0.41
N/A	1.09	1.16	1.01	0.97	0.91	0.58	0.52	0.68	0.54	0.60	0.68	0.68	0.67	0.58	0.64	0.65	0.61	0.50	0.41	0.42	0.39	0.34	0.32
N/A	0.83	2.72	0.98	0.80	0.88	0.82	0.82	0.69	0.50	0.52	0.60	0.63	0.58	0.55	0.50	0.56	0.53	0.48	0.53	0.52	0.40	0.37	N/A
N/A	N/A	1.67	1.06	0.60	0.93	0.85	0.67	1.10	0.59	0.76	0.64	0.67	0.62	0.58	0.51	0.58	0.59	0.55	0.50	0.48	0.50	0.37	N/A
N/A	1.12	0.87	1.04	0.54	0.74	0.72	0.60	0.60	0.42	0.65	0.55	0.53	0.49	0.54	0.58	0.59	0.58	0.54	0.44	0.45	0.43	0.44	N/A
N/A	N/A	1.15	1.87	0.74	0.78	0.81	0.86	0.68	0.60	0.57	0.66	0.62	0.43	0.53	0.56	0.56	0.56	0.50	0.49	0.43	0.47	0.43	N/A
N/A	1.20	1.06	0.65	0.56	0.91	1.00	0.78	0.67	0.65	0.59	0.63	0.59	0.56	0.52	0.53	0.54	0.54	0.51	0.46	0.52	0.48	0.39	N/A
N/A	1.41	1.03	1.42	0.91	0.75	0.62	0.72	0.93	0.67	0.61	0.65	0.56	0.57	0.56	0.53	0.52	0.50	0.52	0.51	0.45	0.39	0.39	0.46
N/A	1.82	0.69	1.00	0.72	0.88	0.62	1.02	0.82	0.52	0.59	0.56	0.49	0.63	0.48	0.52	0.44	0.48	0.49	0.47	0.44	0.39	0.37	0.41
N/A	0.94	0.81	0.97	1.28	0.98	0.60	0.55	0.81	N/A	0.63	0.52	0.39	0.48	0.52	0.52	0.50	0.51	0.41	0.41	0.38	0.37	0.32	0.24
N/A	0.80	0.47	1.21	1.51	0.98	0.82	0.80	0.69	0.59	0.65	0.57	0.40	0.47	0.39	0.47	0.52	0.43	0.43	0.37	0.34	0.31	0.27	0.24
N/A	1.51	1.01	0.89	0.89	0.72	0.61	0.65	0.85	0.64	0.83	0.68	0.67	0.52	0.56	0.54	0.51	0.53	0.46	0.48	0.43	0.38	0.38	0.34
N/A	1.44	0.69	0.74	0.58	0.57	0.80	0.79	0.57	0.55	0.59	0.62	0.58	0.47	0.61	0.58	0.58	0.54	0.56	0.46	0.36	0.43	0.38	N/A
N/A	1.03	0.45	0.74	0.66	0.98	0.49	0.61	0.66	0.55	0.37	0.61	0.57	0.57	0.59	0.52	0.56	0.56	0.49	0.49	0.45	0.41	0.37	N/A
N/A	1.57	0.86	0.48	0.51	0.70	1.08	0.70	0.80	0.64	0.57	0.52	0.60	0.50	0.49	0.47	0.46	0.53	0.50	0.51	0.47	0.41	0.38	N/A
N/A	1.16	0.63	0.77	0.93	0.76	1.27	0.69	0.79	0.62	0.63	0.78	0.52	0.49	0.51	0.47	0.53	0.54	0.55	0.54	0.50	0.51	0.42	N/A
N/A	N/A	0.96	1.02	0.80	0.75	0.66	0.79	0.74	0.69	0.63	1.53	0.45	0.54	0.56	0.67	0.54	0.54	0.54	0.49	0.44	0.45	0.41	N/A
N/A	1.92	0.68	1.01	1.64	1.02	0.71	0.78	0.67	0.68	0.60	0.54	0.63	0.49	0.45	0.49	0.60	0.56	0.43	0.45	0.45	0.40	0.33	0.35

B.5 Studentersamfundet - Knaus



Measurement log - reverberation time

Location: STUDENTERSAMFUNDET - KNAUS	**Excitation:** ☐ Impulse ☒ Noise ☐ Swept Sine
Date: 01.03.2021	**Measurements by:** MORTEN A. EDVARDSEN

Floor plan and source positions:

Room height:

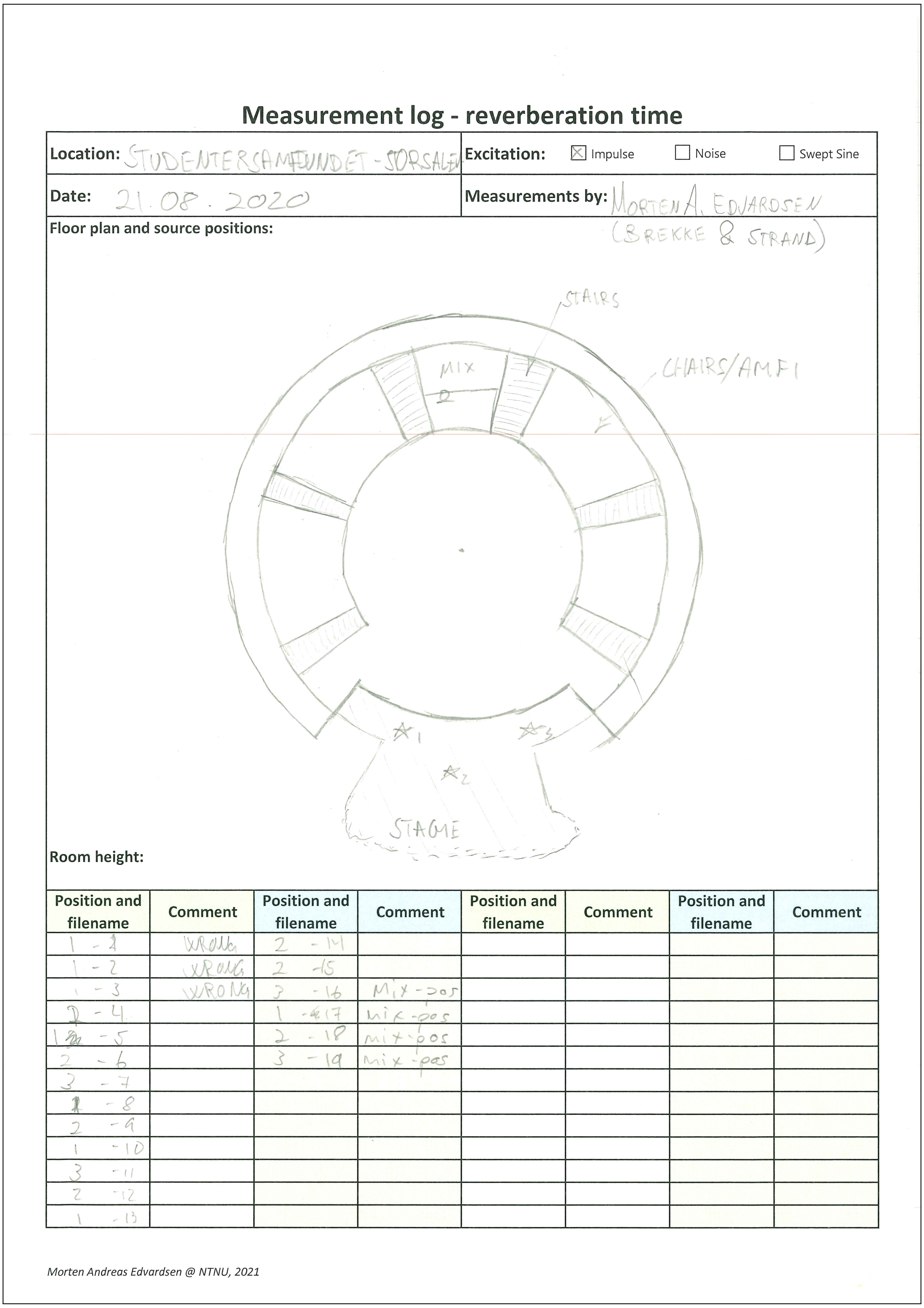
Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1 - 36		2 - 47		3 - 57		x - 67	
1 - 37		2 - 48		3 - 58		x - 68	
1 - 38		2 - 49		3 - 59		PA - 69	Left - WC Pos
1 - 39		2 - 50		3 - 60		PA - 70	Right - WC Pos
1 - 40		2 - 51		3 - 61			
1 - 41		2 - 52		3 - 62			
1 - 42		2 - 53		3 - 63			
1 - 43		2 - 54		3 - 64			
1 - 44		2 - 55	Same pos. as WC	3 - 65	Same pos. as WC		
1 - 45		2 - 56		3 - 66			
1 - 46	Same pos as WC						

Morten Andreas Edvardsen @ NTNU, 2021

Table B.5: Measurements of T_{20} from Studentersamfundet - Knaus

T20 [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
N/A	0.62	0.28	0.61	0.57	0.54	0.41	0.67	0.64	0.26	0.49	0.54	0.67	0.53	0.70	0.64	0.56	0.52	0.55	0.51	0.49	0.43	0.42	0.37
N/A	3.34	0.45	0.38	0.51	0.51	0.40	0.80	0.51	0.40	0.38	0.43	0.47	0.55	0.59	0.52	0.60	0.51	0.54	0.49	0.43	0.40	0.39	0.44
N/A	0.32	0.25	0.57	0.56	0.76	0.67	0.78	0.57	0.33	0.50	0.45	0.69	0.72	0.65	0.54	0.57	0.61	0.56	0.52	0.51	0.44	0.40	0.36
N/A	0.46	0.40	0.74	0.50	0.58	0.65	0.47	0.47	0.38	0.49	0.48	0.64	0.53	0.62	0.56	0.58	0.47	0.50	0.52	0.45	0.44	0.39	0.41
N/A	0.53	0.72	0.81	0.64	0.34	0.41	0.52	0.44	0.46	0.53	0.37	0.51	0.55	0.65	0.58	0.58	0.50	0.52	0.51	0.46	0.45	0.42	0.35
N/A	0.56	0.42	0.57	0.82	0.64	0.87	1.04	0.39	0.46	0.51	0.53	0.56	0.57	0.58	0.62	0.54	0.57	0.51	0.48	0.45	0.39	0.40	0.31
N/A	0.50	0.31	0.34	0.82	0.63	0.56	0.55	0.55	0.52	0.52	0.47	0.49	0.57	0.66	0.65	0.60	0.50	0.53	0.52	0.49	0.43	0.40	0.40
N/A	0.56	0.38	0.46	0.51	0.60	0.68	0.61	0.38	0.52	0.36	0.49	0.61	0.47	0.62	0.62	0.56	0.55	0.51	0.49	0.51	0.43	0.41	0.38
N/A	N/A	0.78	0.70	0.53	1.55	0.64	1.30	0.53	0.64	0.42	0.51	0.53	0.64	0.60	0.52	0.53	0.56	0.54	0.52	0.44	0.46	0.40	0.33
N/A	0.45	0.47	0.44	0.55	0.48	0.55	0.59	0.53	0.37	0.41	0.41	0.47	0.64	0.53	0.52	0.44	0.51	0.44	0.45	0.43	0.46	0.42	0.36
N/A	0.31	0.41	0.19	0.46	0.77	0.39	0.42	0.49	0.57	0.45	0.45	0.46	0.58	0.52	0.52	0.54	0.54	0.53	0.45	0.49	0.45	0.41	0.38
N/A	N/A	0.71	0.62	0.52	0.46	0.40	0.86	0.47	0.46	0.51	0.42	0.55	0.48	0.55	0.55	0.59	0.55	0.52	0.47	0.48	0.48	0.41	0.42
N/A	0.48	0.41	0.44	0.51	0.43	0.54	0.36	0.75	0.47	0.51	0.44	0.67	0.67	0.56	0.59	0.62	0.52	0.48	0.47	0.46	0.44	0.42	0.38
N/A	0.60	0.55	0.48	0.74	0.30	0.43	0.45	0.57	0.37	0.34	0.45	0.46	0.57	0.58	0.65	0.53	0.53	0.53	0.53	0.52	0.42	0.38	0.37
N/A	0.42	0.52	0.49	0.39	0.79	0.75	0.45	0.52	0.48	0.50	0.49	0.47	0.65	0.60	0.56	0.59	0.44	0.52	0.51	0.44	0.45	0.41	0.41
N/A	N/A	0.48	0.47	0.51	0.35	1.21	0.58	0.51	0.41	0.50	0.42	0.50	0.52	0.53	0.61	0.60	0.58	0.52	0.42	0.46	0.44	0.42	0.39
N/A	0.58	0.37	0.51	0.72	0.58	0.54	0.39	0.47	0.46	0.42	0.43	0.51	0.66	0.53	0.59	0.57	0.53	0.51	0.48	0.48	0.46	0.44	0.37
N/A	N/A	0.46	0.42	0.41	0.49	0.58	0.53	0.59	0.44	0.43	0.41	0.53	0.64	0.61	0.58	0.65	0.59	0.49	0.48	0.45	0.41	0.42	0.39
N/A	0.51	0.26	0.45	0.64	0.36	0.66	0.42	0.51	0.78	0.42	0.57	0.63	0.53	0.49	0.53	0.58	0.61	0.55	0.47	0.45	0.40	0.35	0.38
1.35	0.30	0.34	0.28	0.47	0.58	0.70	0.70	0.50	0.35	0.28	0.43	0.53	0.55	0.66	0.62	0.51	0.56	0.51	0.49	0.45	0.42	0.38	0.39
N/A	0.65	0.57	0.66	0.48	0.84	1.10	0.64	0.70	0.45	0.42	0.47	0.54	0.59	0.60	0.55	0.56	0.57	0.52	0.49	0.48	0.42	0.42	0.35
N/A	N/A	0.37	0.68	0.60	0.58	0.57	0.63	0.51	0.44	0.35	0.52	0.66	0.51	0.61	0.64	0.60	0.60	0.53	0.50	0.47	0.40	0.41	0.33
N/A	0.30	0.29	0.50	0.34	0.52	0.90	1.02	0.50	0.54	0.39	0.53	0.46	0.40	0.58	0.48	0.55	0.54	0.50	0.45	0.48	0.42	0.39	0.39
N/A	0.51	0.29	0.36	0.44	0.42	0.73	0.52	0.74	0.39	0.53	0.47	0.47	0.52	0.64	0.59	0.51	0.54	0.53	0.53	0.49	0.43	0.42	0.36
N/A	0.74	0.38	0.37	0.68	0.67	0.69	0.72	0.54	0.56	0.43	0.47	0.50	0.52	0.45	0.63	0.53	0.50	0.48	0.48	0.48	0.43	0.42	0.38
N/A	0.55	0.32	0.33	0.54	0.58	0.80	0.56	0.74	0.54	0.39	0.46	0.45	0.55	0.68	0.48	0.56	0.52	0.53	0.45	0.50	0.45	0.40	0.42
N/A	0.48	0.64	0.77	0.69	0.88	0.41	0.52	0.80	0.41	0.52	0.38	0.57	0.52	0.57	0.56	0.57	0.51	0.52	0.49	0.45	0.46	0.43	0.42
N/A	0.31	0.55	0.20	0.50	0.46	0.51	0.45	0.45	0.31	0.34	0.56	0.63	0.62	0.55	0.56	0.60	0.53	0.49	0.49	0.46	0.47	0.40	0.38
N/A	0.39	0.50	0.30	0.58	0.45	0.56	0.49	0.66	0.51	0.39	0.45	0.56	0.42	0.56	0.62	0.49	0.50	0.51	0.50	0.51	0.45	0.39	0.34
N/A	0.59	0.70	0.56	0.45	0.57	0.37	0.60	0.61	0.49	0.28	0.45	0.60	0.50	0.72	0.59	0.53	0.48	0.56	0.48	0.49	0.43	0.39	0.42
N/A	0.63	0.41	0.70	0.69	0.55	0.55	0.60	0.50	0.59	0.44	0.52	0.50	0.50	0.61	0.68	0.61	0.59	0.49	0.53	0.45	0.48	0.42	0.41

B.6 Studentersamfundet - Storsalen



Measurement log - reverberation time

Location: STUDENTERSAMFUNDET - STORSALEN	**Excitation:** ☒ Impulse ☐ Noise ☐ Swept Sine
Date: 21.08.2020	**Measurements by:** MORTEN A. EDVARDSEN (BREKKE & STRAND)

Floor plan and source positions:

Room height:

Position and filename	Comment	Position and filename	Comment	Position and filename	Comment	Position and filename	Comment
1 - 1	WRONG	2 - 14					
1 - 2	WRONG	2 - 15					
1 - 3	WRONG	3 - 16	Mix-pos				
2 - 4		1 - 17	mix-pos				
1 - 5		2 - 18	mix-pos				
2 - 6		3 - 19	mix-pos				
3 - 7							
1 - 8							
2 - 9							
1 - 10							
3 - 11							
2 - 12							
1 - 13							

Morten Andreas Edvardsen @ NTNU, 2021

Table B.6: Measurements of T_{20} from Studentersamfundet - Storsalen

T20 [s] in one-third octave bands [Hz]																							
50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1k**	**1.25k**	**1.6k**	**2k**	**2.5k**	**3.15k**	**4k**	**5k**	**6.3k**	**8k**	**10k**
1.28	1.29	1.15	1.50	1.56	1.20	1.09	0.86	0.92	0.96	0.97	0.94	0.92	0.79	0.77	0.87	0.85	0.86	0.87	0.84	0.82	0.80	0.73	0.63
0.82	1.33	1.56	1.51	1.33	1.34	1.29	1.18	0.95	0.76	0.87	0.91	0.90	0.84	0.88	0.88	0.84	0.86	0.88	0.88	0.87	0.80	0.74	0.63
1.71	1.11	1.27	1.26	1.25	1.21	1.01	1.02	0.81	0.86	0.72	0.79	0.78	0.77	0.85	0.78	0.81	0.84	0.81	0.88	0.83	0.75	0.73	0.65
0.96	1.65	1.53	1.68	1.26	1.02	1.09	0.82	0.67	0.77	0.82	0.87	0.81	0.71	0.90	0.87	0.86	0.82	0.84	0.80	0.80	0.77	0.77	0.65
1.31	1.10	1.55	1.53	1.32	0.93	0.89	0.89	0.74	0.75	0.88	0.94	0.80	0.77	0.86	0.89	0.81	0.82	0.87	0.80	0.79	0.77	0.71	0.62
1.93	1.19	1.49	1.71	1.36	1.28	0.86	1.05	0.75	1.09	0.83	0.68	0.90	0.80	0.76	0.77	0.76	0.73	0.86	0.82	0.82	0.73	0.73	0.61
1.23	1.61	1.21	1.23	1.10	1.02	1.04	0.80	0.77	0.69	0.74	0.69	0.86	0.71	0.75	0.76	0.79	0.75	0.76	0.75	0.75	0.72	0.68	0.57
1.54	1.47	1.28	1.37	1.59	1.26	0.96	0.97	0.71	0.80	0.76	0.84	0.73	0.76	0.77	0.76	0.76	0.73	0.81	0.81	0.74	0.75	0.68	0.61
0.77	0.83	1.35	1.38	1.63	1.24	0.84	0.88	0.89	0.84	0.90	0.80	0.75	0.78	0.81	0.71	0.74	0.81	0.78	0.74	0.75	0.73	0.65	0.54
1.38	0.83	0.73	1.19	1.37	1.27	0.86	0.90	0.71	0.63	0.72	0.82	0.73	0.76	0.75	0.75	0.86	0.77	0.76	0.81	0.77	0.72	0.68	0.56
1.25	1.20	1.17	1.64	1.60	1.06	1.08	1.00	0.71	0.84	0.98	0.97	0.88	0.88	0.83	0.94	0.86	0.90	0.88	0.85	0.85	0.82	0.74	0.65
1.41	1.32	1.28	1.65	1.62	1.19	1.15	1.04	0.84	0.79	0.79	0.92	0.87	0.84	0.79	0.85	0.88	0.89	0.89	0.90	0.82	0.78	0.71	0.68
2.08	0.90	1.05	1.25	1.39	0.85	0.94	1.02	0.82	0.80	0.66	0.70	0.67	0.79	0.73	0.74	0.76	0.75	0.71	0.71	0.69	0.66	0.66	0.58
1.79	0.95	1.36	1.07	1.15	1.03	0.99	0.90	0.72	0.80	0.77	0.78	0.75	0.79	0.77	0.79	0.77	0.76	0.77	0.75	0.78	0.73	0.67	0.59
1.66	0.97	1.26	1.47	1.33	1.00	0.94	0.94	0.74	0.69	0.72	0.75	0.79	0.77	0.78	0.83	0.78	0.79	0.75	0.80	0.75	0.74	0.68	0.56
1.89	1.25	1.36	1.51	1.32	0.99	0.97	0.97	0.78	0.83	0.67	0.69	0.78	0.83	0.73	0.74	0.76	0.75	0.78	0.77	0.77	0.71	0.63	0.55

Appendix C

Raw data from impulse responses

C.1 Reverberation time, T_{20}

Table C.1: Measurements of T_{20} gained in ODEON from FFT-based deconvolutions of recordings in one position of ESS played through a PA system.

	T20 [s] in octave bands [Hz]							
Venue	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Blå Grotte	1.27	1.14	0.97	0.74	0.72	0.64	0.46	0.41
	1.31	1.14	1.05	0.79	0.73	0.64	0.49	0.37
Cosmopolite	1.41	0.89	0.86	0.87	1.02	1.13	1.13	0.86
	1.08	0.85	0.73	0.86	1.03	1.13	1.08	0.83
Dokkhuset Scene	1.11	1.09	0.94	0.76	0.75	0.78	0.67	0.52
	1.11	1.11	0.84	0.71	0.78	0.77	0.66	0.50
	1.15	1.10	0.94	0.74	0.74	0.80	0.67	0.51
	1.12	1.10	0.82	0.72	0.75	0.76	0.64	0.51
Fosnavåg Konserthus	1.76	0.95	0.76	0.69	0.64	0.69	0.62	0.53
	1.79	1.10	0.81	0.67	0.68	0.67	0.61	0.53
Fana Kulturhus	1.38	0.99	0.74	0.70	0.71	0.61	0.46	0.37
	1.19	1.11	0.77	0.67	0.81	0.60	0.48	0.39
	1.21	1.13	0.78	0.66	0.77	0.62	0.47	0.39
Hamar Kulturhus - Kirsten Flagstad	1.55	1.58	1.11	0.78	0.78	0.78	0.62	0.48
	1.43	1.50	1.05	0.77	0.76	0.80	0.61	0.49
	1.50	1.50	1.12	0.80	0.79	0.77	0.62	0.48
	1.44	1.51	1.03	0.77	0.75	0.80	0.59	0.47
Iris Scene	0.59	0.54	0.65	0.70	0.73	0.69	0.61	0.49
	0.59	0.58	0.62	0.72	0.80	0.72	0.68	0.54
	0.59	0.54	0.63	0.64	0.73	0.68	0.61	0.50
Jernvaren	1.00	0.78	0.51	0.47	0.52	0.53	0.50	0.44
	1.06	0.75	0.52	0.36	0.53	0.52	0.50	0.45
KICK Nattklubb & Scene	0.69	0.58	0.56	0.69	0.73	0.77	0.65	0.60
	0.47	0.61	0.57	0.63	0.71	0.71	0.61	0.49
	0.72	0.59	0.55	0.69	0.73	0.77	0.65	0.59
	0.52	0.62	0.57	0.63	0.72	0.70	0.60	0.49
	0.68	0.58	0.56	0.69	0.75	0.77	0.66	0.60
	0.52	0.63	0.57	0.64	0.72	0.73	0.61	0.49

Table C.1 continued from previous page

Kultursenteret ISAK - Amfisalen	0.91	0.97	0.87	0.79	0.72	0.65	0.55	0.42
	0.96	0.99	0.86	0.74	0.67	0.64	0.52	0.43
	0.92	0.98	0.89	0.79	0.72	0.65	0.54	0.41
	0.99	1.02	0.88	0.75	0.67	0.62	0.51	0.43
Live & Rock Cafe	0.65	0.59	0.54	0.61	0.72	0.79	0.71	0.63
	0.62	0.64	0.55	0.63	0.71	0.83	0.75	0.63
Nasjonal Jazzscene	0.58	0.74	0.73	0.67	0.68	0.71	0.64	0.56
	0.89	0.75	0.69	0.64	0.73	0.69	0.62	0.54
	0.62	0.76	0.75	0.67	0.67	0.70	0.62	0.54
	0.81	0.74	0.70	0.70	0.74	0.70	0.62	0.54
Nidelven Bar & Scene	0.56	0.51	0.50	0.49	0.53	0.53	0.48	0.40
	0.52	0.43	0.40	0.40	0.50	0.54	0.48	0.39
	0.52	0.50	0.48	0.49	0.51	0.54	0.48	0.40
	0.51	0.43	0.41	0.39	0.51	0.56	0.49	0.37
Norges Handelshøyskole - Aulaen	0.95	0.85	1.01	0.89	0.95	1.03	0.75	0.53
	1.00	0.99	0.89	0.81	0.92	0.97	0.77	0.57
Parkteatret	0.81	0.51	0.44	0.42	0.39	0.41	0.37	0.39
	0.80	0.50	0.50	0.37	0.36	0.41	0.42	0.38
	0.83	0.52	0.42	0.42	0.40	0.41	0.38	0.39
	0.79	0.49	0.50	0.38	0.36	0.40	0.43	0.39
Riksscenen - Hovedsalen	1.67	1.21	0.78	0.72	0.72	0.70	0.63	0.60
	1.86	1.10	0.84	0.63	0.65	0.65	0.60	0.60
Sandnes Kulturhus - Storsalen	2.66	1.67	1.58	1.36	1.20	1.10	1.00	0.88
	3.33	1.72	1.38	1.35	1.19	1.14	1.09	0.89
Stormen Konserthus - Lille sal	1.83	0.63	0.72	0.69	0.69	0.68	0.56	0.49
	1.78	0.76	0.72	0.67	0.73	0.66	0.57	0.48
Stormen Konserthus - Sinus	1.10	0.49	0.56	0.56	0.50	0.59	0.56	0.50
	0.70	0.58	0.59	0.60	0.54	0.60	0.57	0.50
Stormen Konserthus - Store sal	1.53	1.27	1.13	1.27	1.35	1.16	1.04	0.77
Studentersamfundet - Klubben	0.75	0.82	0.63	0.52	0.52	0.54	0.51	0.45
	0.77	0.82	0.63	0.57	0.51	0.52	0.49	0.50
	0.73	0.78	0.63	0.52	0.51	0.56	0.51	0.46
	0.77	0.83	0.63	0.57	0.52	0.52	0.49	0.48
Studentersamfundet - Knaus	0.27	0.38	0.55	0.47	0.60	0.58	0.49	0.42
	0.35	0.47	0.50	0.44	0.56	0.58	0.51	0.43
	0.27	0.39	0.55	0.47	0.59	0.59	0.49	0.45
	0.35	0.47	0.51	0.45	0.55	0.57	0.50	0.45
	0.28	0.39	0.55	0.48	0.58	0.60	0.49	0.44
	0.38	0.49	0.51	0.44	0.55	0.59	0.50	0.43
Studentersamfundet - Storsalen	1.33	1.24	0.88	0.73	0.74	0.71	0.64	0.54
	1.33	1.21	0.87	0.74	0.76	0.72	0.63	0.53
	1.51	1.24	0.87	0.74	0.76	0.73	0.64	0.52
	1.36	1.17	0.88	0.75	0.75	0.73	0.64	0.54
Studenthuset City Scene	0.76	0.67	0.65	0.49	0.50	0.50	0.45	0.41
	0.68	0.77	0.44	0.41	0.49	0.45	0.45	0.42
Støperiet Scene	1.31	0.83	0.89	0.78	0.84	0.85	0.73	0.59
	1.45	0.93	0.88	0.75	0.80	0.83	0.71	0.60
Tvibit Ungdomshus	0.54	0.42	0.40	0.44	0.40	0.45	0.42	0.37

Table C.1 continued from previous page

	0.35	0.28	0.38	0.43	0.41	0.45	0.45	0.40
	0.53	0.45	0.41	0.44	0.42	0.45	0.42	0.37
	0.35	0.29	0.38	0.41	0.42	0.46	0.45	0.40
Vulkan Arena	1.55	1.04	0.95	0.76	0.80	0.77	0.69	0.57
	1.04	1.41	1.02	0.75	0.74	0.71	0.62	0.54
	1.54	1.07	0.97	0.78	0.80	0.79	0.71	0.59
	1.07	1.40	1.11	0.82	0.77	0.72	0.64	0.54
	1.58	1.09	0.98	0.79	0.79	0.77	0.70	0.61
Stavanger Konserthus - Zetlitz	1.90	1.66	1.37	1.21	1.33	1.05	0.94	0.77
	1.70	1.50	1.33	1.14	1.42	1.04	0.92	0.87

C.2 Early decay time, EDT

Table C.2: Measurements of EDT gained in ODEON from FFT-based deconvolutions of recordings in one position of ESS played through a PA system.

	EDT [s] in octave bands [Hz]							
Venue	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Blå Grotte	1.18	1.26	0.86	0.66	0.55	0.30	0.30	0.27
	1.47	1.21	0.87	0.73	0.65	0.42	0.27	0.23
Cosmopolite	0.83	0.78	0.66	0.69	0.79	1.04	1.09	0.70
	0.90	0.56	0.76	0.76	0.90	1.03	1.01	0.77
Dokkhuset Scene	0.95	0.89	0.66	0.66	0.81	0.64	0.55	0.25
	0.94	0.90	0.67	0.71	0.79	0.62	0.56	0.26
	0.94	0.94	0.86	0.74	0.74	0.65	0.58	0.26
	0.95	0.95	0.84	0.72	0.72	0.65	0.57	0.20
Fana Kulturhus	1.39	0.63	0.38	0.41	0.40	0.24	0.28	0.08
	1.34	0.70	0.34	0.37	0.34	0.30	0.33	0.10
	1.30	0.69	0.34	0.40	0.36	0.26	0.29	0.09
Fosnavåg Konserthus	1.34	0.87	0.70	0.50	0.33	0.32	0.48	0.38
	1.17	0.78	0.59	0.44	0.40	0.43	0.51	0.36
Hamar Kulturhus - Kirsten Flagstad	1.11	1.18	0.79	0.32	0.29	0.29	0.25	0.13
	1.11	1.19	0.77	0.31	0.28	0.25	0.25	0.13
	1.13	1.31	0.62	0.41	0.36	0.21	0.23	0.18
	1.14	1.31	0.64	0.45	0.38	0.23	0.25	0.21
Iris Scene	0.31	0.48	0.40	0.38	0.43	0.50	0.50	0.36
	0.54	0.39	0.40	0.42	0.48	0.49	0.50	0.24
	0.33	0.48	0.41	0.36	0.43	0.43	0.48	0.36
Jernvaren	1.03	0.70	0.42	0.31	0.47	0.39	0.35	0.27
	0.86	0.77	0.40	0.30	0.45	0.31	0.37	0.29
KICK Nattklubb & Scene	0.74	0.40	0.46	0.60	0.66	0.72	0.64	0.07
	0.75	0.40	0.46	0.57	0.65	0.77	0.63	0.07
	0.74	0.40	0.46	0.59	0.63	0.75	0.64	0.07
	0.79	0.51	0.44	0.66	0.65	0.81	0.73	0.40
	0.79	0.54	0.46	0.69	0.63	0.76	0.69	0.41
	0.79	0.52	0.45	0.70	0.65	0.77	0.70	0.41
Kultursenteret ISAK - Amfisalen	1.07	0.72	0.62	0.66	0.63	0.26	0.31	0.23
	1.07	0.73	0.63	0.67	0.62	0.24	0.32	0.25
	0.79	0.70	0.66	0.59	0.50	0.30	0.33	0.24
	0.79	0.70	0.66	0.59	0.48	0.30	0.31	0.24
Live & Rock Cafe	0.57	0.59	0.74	0.76	0.68	0.58	0.54	0.39
	0.52	0.56	0.65	0.70	0.66	0.62	0.58	0.46
Nasjonal Jazzscene	0.56	0.52	0.63	0.26	0.17	0.61	0.50	0.25
	0.55	0.53	0.58	0.20	0.16	0.58	0.52	0.25
	0.76	0.77	0.56	0.67	0.59	0.66	0.67	0.54
	0.73	0.73	0.49	0.58	0.56	0.65	0.64	0.52
Nidelven Bar & Scene	0.49	0.65	0.37	0.44	0.40	0.32	0.38	0.27
	0.52	0.66	0.39	0.46	0.44	0.36	0.37	0.27
	0.43	0.41	0.52	0.39	0.40	0.41	0.40	0.29
	0.43	0.41	0.49	0.39	0.42	0.38	0.40	0.31
Norges Handelshøyskole - Aulaen	0.93	0.94	0.63	0.41	0.67	0.81	0.52	0.32
	0.72	0.69	0.66	0.48	0.71	0.88	0.50	0.22

Table C.2 continued from previous page

Parkteatret	0.49	0.49	0.46	0.39	0.38	0.31	0.35	0.30
	0.50	0.49	0.46	0.38	0.40	0.33	0.35	0.31
	0.51	0.53	0.34	0.32	0.35	0.40	0.37	0.26
	0.52	0.53	0.34	0.32	0.36	0.42	0.37	0.28
Riksscenen - Hovedsalen	1.10	0.64	0.62	0.37	0.61	0.67	0.53	0.19
	1.38	0.82	0.47	0.46	0.52	0.51	0.38	0.11
Sandnes Kulturhus - Storsalen	1.90	0.53	0.46	0.84	0.82	1.06	0.91	0.47
	1.65	0.92	0.60	0.56	0.81	1.15	0.70	0.35
Stormen Konserthus - Lille sal	0.81	0.42	0.34	0.42	0.40	0.43	0.42	0.25
	1.36	0.68	0.43	0.41	0.36	0.28	0.28	0.23
Stormen Konserthus - Sinus	0.58	0.42	0.23	0.39	0.26	0.38	0.39	0.22
	0.77	0.49	0.37	0.29	0.41	0.43	0.34	0.25
Stormen Konserthus - Store sal	1.19	1.21	0.57	0.87	0.91	0.97	0.74	0.38
Studentersamfundet - Klubben	0.93	1.06	0.50	0.41	0.50	0.26	0.45	0.43
	0.93	1.03	0.52	0.42	0.49	0.28	0.46	0.43
	0.92	0.86	0.66	0.43	0.55	0.23	0.46	0.36
	0.94	0.85	0.66	0.46	0.55	0.21	0.46	0.41
Studentersamfundet - Knaus	0.50	0.56	0.44	0.37	0.45	0.48	0.51	0.40
	0.50	0.57	0.45	0.38	0.45	0.49	0.49	0.39
	0.49	0.56	0.44	0.37	0.45	0.49	0.52	0.39
	0.44	0.40	0.49	0.43	0.53	0.57	0.50	0.39
	0.43	0.40	0.48	0.43	0.52	0.57	0.51	0.39
	0.44	0.41	0.49	0.43	0.53	0.52	0.52	0.39
Studentersamfundet - Storsalen	0.95	0.75	0.45	0.35	0.32	0.26	0.28	0.25
	0.96	0.74	0.45	0.32	0.31	0.25	0.27	0.25
	0.95	0.68	0.46	0.35	0.31	0.24	0.28	0.25
	0.98	0.75	0.46	0.31	0.31	0.25	0.27	0.24
Studenthuset City Scene	0.57	0.61	0.23	0.44	0.34	0.43	0.38	0.24
	0.45	0.52	0.41	0.32	0.30	0.13	0.08	0.03
Støperiet Scene	1.28	0.96	0.80	0.88	0.54	0.48	0.57	0.31
	1.40	1.10	0.77	0.91	0.54	0.59	0.55	0.33
Tvibit Ungdomshus	0.52	0.72	0.35	0.37	0.39	0.39	0.42	0.35
	0.52	0.76	0.36	0.37	0.40	0.42	0.43	0.36
	0.40	0.41	0.31	0.34	0.36	0.35	0.35	0.24
	0.41	0.41	0.31	0.34	0.35	0.35	0.35	0.25
Vulkan Arena	1.19	1.18	1.11	0.48	0.46	0.70	0.52	0.36
	1.05	1.18	0.84	0.44	0.43	0.58	0.50	0.40
	1.05	1.19	0.85	0.45	0.43	0.56	0.53	0.39
	1.21	1.11	1.02	0.45	0.49	0.61	0.57	0.39
	1.24	1.14	0.99	0.43	0.43	0.63	0.57	0.36
Stavanger Konserthus - Zetlitz	1.83	1.13	1.15	0.74	0.88	0.71	0.61	0.11
	1.62	1.10	1.41	0.99	0.83	1.11	0.71	0.31

C.3 Definition, D_{50}

Table C.3: Measurements of D_{50} gained in ODEON from FFT-based deconvolutions of recordings in one position of ESS played through a PA system.

	D_{50} [-] in octave bands [Hz]							
Venue	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Blå Grotte	0.41	0.40	0.59	0.69	0.81	0.89	0.89	0.91
	0.55	0.54	0.68	0.74	0.83	0.89	0.91	0.94
Cosmopolite	0.65	0.79	0.64	0.84	0.86	0.79	0.64	0.81
	0.70	0.87	0.83	0.76	0.77	0.80	0.77	0.83
Dokkhuset Scene	0.51	0.40	0.78	0.77	0.76	0.77	0.83	0.93
	0.50	0.41	0.77	0.71	0.75	0.77	0.83	0.92
	0.48	0.37	0.75	0.69	0.67	0.72	0.81	0.92
	0.46	0.35	0.73	0.72	0.74	0.79	0.86	0.93
Fana Kulturhus	0.48	0.82	0.91	0.91	0.88	0.94	0.94	0.98
	0.38	0.77	0.90	0.89	0.89	0.92	0.91	0.96
	0.40	0.79	0.92	0.92	0.90	0.94	0.93	0.97
Fosnavåg Konserthus	0.40	0.61	0.79	0.87	0.88	0.87	0.80	0.85
	0.45	0.72	0.87	0.89	0.90	0.90	0.86	0.87
Hamar Kulturhus - Kirsten Flagstad	0.62	0.41	0.81	0.90	0.91	0.91	0.92	0.96
	0.60	0.38	0.83	0.93	0.93	0.94	0.92	0.95
	0.69	0.45	0.83	0.91	0.89	0.92	0.92	0.95
	0.71	0.50	0.87	0.91	0.90	0.93	0.93	0.95
Iris Scene	0.82	0.64	0.63	0.60	0.52	0.54	0.59	0.66
	0.85	0.86	0.90	0.86	0.79	0.82	0.82	0.91
	0.91	0.84	0.84	0.83	0.85	0.88	0.81	0.89
Jernvaren	0.49	0.57	0.80	0.91	0.82	0.86	0.87	0.91
	0.57	0.65	0.87	0.91	0.82	0.88	0.87	0.91
KICK Nattklubb & Scene	0.82	0.91	0.86	0.83	0.82	0.85	0.85	0.95
	0.81	0.91	0.86	0.84	0.84	0.89	0.90	0.96
	0.81	0.91	0.86	0.83	0.82	0.84	0.84	0.95
	0.52	0.91	0.90	0.77	0.77	0.67	0.71	0.85
	0.52	0.90	0.89	0.81	0.79	0.66	0.74	0.86
	0.52	0.90	0.90	0.82	0.79	0.66	0.73	0.86
Kultursenteret ISAK - Amfisalen	0.63	0.75	0.69	0.75	0.75	0.90	0.89	0.92
	0.68	0.81	0.78	0.75	0.79	0.92	0.90	0.93
	0.55	0.70	0.74	0.74	0.80	0.89	0.88	0.92
	0.56	0.70	0.73	0.75	0.82	0.89	0.89	0.92
Live & Rock Cafe	0.51	0.42	0.43	0.47	0.68	0.79	0.82	0.87
	0.60	0.43	0.41	0.54	0.67	0.75	0.81	0.85
Nasjonal Jazzscene	0.80	0.81	0.81	0.94	0.94	0.84	0.87	0.93
	0.78	0.77	0.82	0.95	0.96	0.83	0.85	0.92
	0.51	0.69	0.77	0.61	0.70	0.68	0.70	0.78
	0.50	0.69	0.77	0.62	0.71	0.68	0.72	0.80
Nidelven Bar & Scene	0.87	0.81	0.91	0.82	0.84	0.89	0.87	0.92
	0.85	0.76	0.80	0.74	0.75	0.82	0.84	0.90
	0.86	0.81	0.83	0.80	0.83	0.83	0.84	0.91
	0.86	0.81	0.83	0.80	0.82	0.85	0.85	0.90
Norges Handelshøyskole - Aulaen	0.56	0.56	0.84	0.87	0.72	0.67	0.76	0.87
	0.62	0.68	0.86	0.90	0.86	0.75	0.85	0.92

Table C.3 continued from previous page

Parkteatret	0.74	0.81	0.86	0.89	0.85	0.88	0.85	0.89
	0.74	0.81	0.85	0.88	0.82	0.86	0.85	0.89
	0.68	0.83	0.91	0.93	0.87	0.81	0.85	0.91
	0.68	0.83	0.91	0.93	0.85	0.79	0.84	0.90
Riksscenen - Hovedsalen	0.51	0.71	0.80	0.88	0.83	0.79	0.88	0.93
	0.62	0.78	0.80	0.86	0.80	0.80	0.87	0.95
Sandnes Kulturhus - Storsalen	0.53	0.91	0.93	0.85	0.82	0.81	0.83	0.90
	0.49	0.85	0.91	0.87	0.80	0.81	0.83	0.89
Stormen Konserthus - Lille sal	0.75	0.87	0.91	0.85	0.87	0.88	0.89	0.92
	0.71	0.84	0.87	0.86	0.87	0.89	0.90	0.92
Stormen Konserthus - Sinus	0.70	0.85	0.93	0.87	0.90	0.84	0.84	0.92
	0.68	0.62	0.90	0.90	0.83	0.81	0.86	0.90
Stormen Konserthus - Store sal	0.55	0.69	0.86	0.82	0.79	0.81	0.82	0.88
Studentersamfundet - Klubben	0.43	0.86	0.84	0.81	0.79	0.90	0.82	0.85
	0.44	0.85	0.83	0.78	0.81	0.90	0.80	0.85
	0.33	0.75	0.62	0.78	0.79	0.90	0.84	0.87
	0.35	0.77	0.65	0.78	0.86	0.94	0.86	0.87
Studentersamfundet - Knaus	0.87	0.83	0.76	0.80	0.79	0.80	0.79	0.85
	0.85	0.80	0.75	0.82	0.83	0.82	0.79	0.85
	0.87	0.84	0.81	0.84	0.82	0.81	0.81	0.87
	0.91	0.84	0.77	0.82	0.80	0.82	0.80	0.86
	0.91	0.84	0.77	0.82	0.80	0.82	0.85	0.86
	0.89	0.81	0.71	0.78	0.69	0.75	0.78	0.85
Studentersamfundet - Storsalen	0.34	0.64	0.90	0.86	0.90	0.92	0.91	0.94
	0.32	0.66	0.85	0.85	0.87	0.91	0.91	0.93
	0.37	0.63	0.87	0.87	0.89	0.91	0.91	0.94
	0.34	0.64	0.90	0.88	0.91	0.92	0.92	0.94
Studenthuset City Scene	0.79	0.88	0.92	0.86	0.93	0.90	0.92	0.95
	0.92	0.92	0.93	0.94	0.94	0.96	0.96	0.98
Støperiet Scene	0.46	0.49	0.78	0.68	0.74	0.87	0.81	0.91
	0.28	0.40	0.71	0.68	0.67	0.77	0.77	0.89
Tvibit Ungdomshus	0.79	0.62	0.89	0.86	0.77	0.79	0.77	0.84
	0.76	0.56	0.88	0.84	0.75	0.78	0.77	0.83
	0.86	0.84	0.91	0.89	0.84	0.88	0.88	0.92
	0.86	0.85	0.86	0.85	0.81	0.86	0.87	0.91
Vulkan Arena	0.40	0.43	0.77	0.89	0.88	0.83	0.86	0.90
	0.41	0.46	0.83	0.89	0.88	0.85	0.82	0.85
	0.40	0.45	0.83	0.89	0.88	0.87	0.82	0.86
	0.39	0.48	0.78	0.86	0.87	0.83	0.84	0.89
	0.36	0.42	0.76	0.88	0.87	0.82	0.83	0.88
Stavanger Konserthus - Zetlitz	0.30	0.27	0.52	0.76	0.63	0.76	0.80	0.95
	0.67	0.50	0.77	0.82	0.55	0.76	0.81	0.89

Appendix D

Matlab code: Calculate impulse response

```matlab
function IR_from_RR(outputsig,inputsig,fs,ir_path)

%--------------------------------%
%   Morten Andreas Edvardsen     %
%   NTNU, 2021                   %
%--------------------------------%

%This script generates an impulse response from a given reference signal
%and a measurement of that signal. The measurement must be of an
%appropriate time interval in order for this function to give usable
%results.

    % meassig = measurement signal [nx1 double]
    % refsig = reference signal [nx1 double]
    % fs = sampling frequency
    % ir_path = where to store the generated impulse response

%Filtering the measured signal
outputsig = highpass(outputsig, 20,fs);
outputsig = lowpass(outputsig, 20000,fs);

%Defining length of fft
nfft = 2^(nextpow2(max([length(outputsig) length(inputsig)])));

%fft of both signals
x = fft(inputsig,nfft);
y = fft(outputsig,nfft);

%Deconvolution and ifft.
h = real(ifft(y./x));

%Write IR to .wav-file
audiowrite(ir_path,h,fs,'BitsPerSample',32)
end
```

Appendix E

Matlab code: Statistical analysis

```
function [a,b,r,p,fig] = linear_stat_analysis(x,y,nameofxvar,nameofyvar)

%-------------------------------%
%   Morten Andreas Edvardsen    %
%   NTNU, 2021                  %
%-------------------------------%

%This function generates a least squares regression line, y = a + bx, to
% two datasets, x and y, while computing the correlation coefficient, r and
% the p-value used for determining statistical significance. In addition,
% a figure using the LaTeX interpreter is generated to visualise results.
% "nameofxvar" and "nameofyvar" gives the label for the x and y axis, and
% should be entered as a string.

% Tested to work with MATLAB r2021a

q = polyfit(x,y,1); %Calculating the regression line
px = [min(x) max(x)];
py = polyval(q,px);

[r,p] = corrcoef(x,y); %Calculating r and p

a = q(1);
b = q(2);
r = r(1,2);
p = p(1,2);

fig = figure();
scatter(x,y,'filled')
hold on
plot(px,py)
grid on
xlabel(nameofxvar)
ylabel(nameofyvar)
legend('Measured levels','Least Squares Regression')
str=sprintf('r = %1.2f, p = %1.4f',r,p);
dim = [.08 0 0 .22];
annotation('textbox',dim,'String',str,'FitBoxToText','on','EdgeColor', [1 1 1]);
set(findall(gcf,'-property','Interpreter'),'Interpreter','latex')
end
```

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