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A study of sound reflection patterns in studio and control rooms

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Abstract

The Master thesis investigates sound reflection patterns in studio and control rooms. Five studio and control rooms from Sveriges Radio at Kanalhuset were chosen for this purpose. Measurements and room acoustical calculations have been performed and will be compared to each other. The results are analyzed by judging the agreement of calculation and measurement as well as the studio quality.

Keywords: Room acoustics, computer modeling, small rooms, reflection patterns

Contents

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Notations

Abbreviation	Description	Unit
CEC	Cumulative energy curve	dB
EDT	Early decay time	s
ETC	Energy time curve	dB
f	Frequency	Hz
FR	Frequency response	dB
IR, g(t)	Impulse response	Pa
t, τ	Time	s
T20, T30	Reverberation times	s
ω	Angular frequency	rad/s

1 Introduction

My interest for this topic came hand in hand with a course in room acoustics at Chalmers where we competed in an American competition. The aim was to design a building that housed a hotel, office and nightclub.
In order to get good acoustics in these various part of the building, I used the room acoustical calculation program "'CATT acoustics"'.

I wanted to study CATT more in detail and was interested how much correspondence you would get in reality.
So, when choosing my topic I wanted to compare measurements and calculations.

Together with my supervisor Mendel, we chose to study studio and control rooms in the Kanalhuset which houses the Swedish Radio.

Studio and control rooms are rather small rooms when compared to an opera or concert hall. The calculation of such small rooms is often deviating more from measurements than calculations for bigger rooms.
The thesis compares results from the measurement and calculation of the impulse response of the rooms. The rooms are studied with the aspect of sound reflection patterns in the rooms.

Studio and control rooms have often to fulfill two means: they should enable a sound monitoring on a high level but also adapt the sound perception of a piece to a domestic living room where then end customer sits.
The chosen rooms are judged upon their quality.

The thesis opens with a theoretical background on human sound perception including psychoacoustic effects such as the Haas effect. The model of geometrical acoustics used for the calculation is explained. Furthermore, a short background to the basic principle of studio and control rooms is given.

In the method part, I introduce the studied rooms as well as the measurement and calculation principles.

The results are shown for all five studio and control rooms as a comparison between measurement and calculation. They are later explained in the Discussion part.

The conclusion summarized the findings of my study and names some feedback that I received during my thesis presentation.

2 Theory

2.1 Human perception of sound

In the past, it was of vital importance for humans to know from which direction a sound came from in order to be e.g. prepared for an attack. The procedure of analyzing where the sound originates from is called localization.
For sound localization, two factors are considered to be most important: the interaural time delay (ITD) between the two ears and the interaural level difference (ILD) created by the interaction of the head and the ears [1].

Because of our anatomical position of the ears we perceive sound differently depending on the angle of incidence. Sound is furthermore scattered by the torso, especially by the shoulders.

In acoustics, it has been proven to be most practical to use a head-related coordinate system (see figure 1). The horizontal plane is located at the height of the ear canal and the vertical plan is centered at the axis of the entrance of the ear canal.

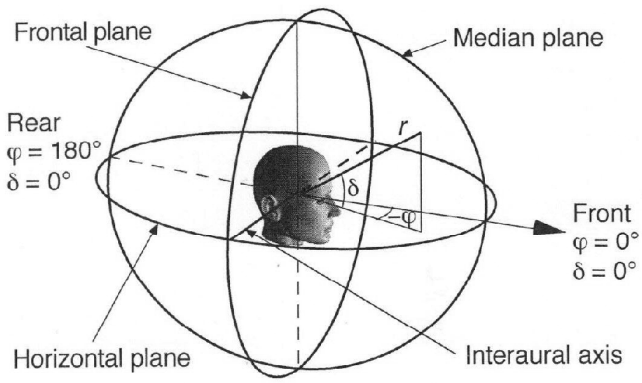


Figure 1: Head-realted coordinate system [1]

When sound is originated to the left of the head, it arrives around 1 ms earlier at the left than at right ear (ITD). Hereby, the mid and high frequency components (which have shorter wavelengths) are shielded off by the head so that they are perceived less loud at the right ear (ILD).

The ILD is much frequency dependent since the lower frequencies with long wavelengths bend around the head whereas shorter wavelengths are reflected. For frequencies above 2 kHz, the ILD improves our ability to locate sources in the horizontal plane. For frequencies that have a wavelength that is shorter than the diameter of the head, the ILD can become very large, reaching more than 20 dB.

At frequencies below 1 kHz, it is the ITD which is dominant for localization using the phase difference between the sounds at our ears.

Often, we adjust our head by small movements if we have difficulties in determining the location of the sound source.

The apparent direction of a sound that is originated by two loudspeakers can be changed by adjusting the level or the delay of one of the loudspeakers. In the early days, loudspeakers were often placed in a 90° angle [2]. Nowadays, a 60° angle placement is preferred because the error in the perceived sound direction decreases significantly. This can be explained by the brain's weak ability to judge time delays in the vertical plane (is that true?).

Humans are able to localize a sound event at a direction that is different from the true sound location. This is most obvious with headphones. Though the true sound is originated directly at the ears, we perceive the sound coming from outside or even from inside the head.

Loud speech is perceived as more distant whereas whispering is always associated to short distances [1]. This special perception though is related to cognition. We are used to shout if we are far away. Thus if we hear someone shouting, we automatically assume that the true sound source is distant.

As for headphones, the true distance for loudspeaker playback (the distance between loudspeaker and listener) often does not correspond to the perceived distance [1]. A recorded orchestra e.g. has many instruments and the loudspeakers can impossibly represent all instrument locations at all time.
Furthermore, recording of an orchestra is done by using several microphones that capture several instruments at the same time. Hence, when played back, each loudspeaker reproduces several instruments.

2.2 Haas effect

Additionally to the described anatomical and acoustical processes that allow our ears to localize a sound source, one should not neglect the psychoacoustical effects.

One of the most important ones is the precedence effect.
The precedence effect is based on the law of the first wave front which was defined by Cremer in 1948 [3].
Two loudspeakers were placed 90° apart from each other and sent out a non-periodic, coherent signal. The listener, facing the loudspeakers, sat at a 3 m distance on the median line of the loudspeakers. When both sources radiated at the same time and same level, the sound event appeared to be just in front of the listener. If one of the loudspeakers was then delayed, the sound event shifted location towards the earlier radiating loudspeaker.

In 1949 Wallach extended the law of the first wave front to the precedence effect [2]. The precedence effect tells us that humans are able to localize a sound source based on the first arriving sound if the second is present within a certain delay range. This delay range is much signal dependent. For speech the two sound sources merge for a delay time below 50 ms, for music below 100 ms. If the second sound arrives later, two distinct sounds are heard, refered to as echo.

In 1951, Haas added further information to the law of the first wave front or precedence effect [4]. As Haas effect is known that the precedence effect is even true if the second sound has an increased level of 10 dB. Although then, the delay range decreases to 10 ms for speech and 30 ms for music.

All three linked effects are used in sound reinforcement systems in bigger rooms. If a sound originates from a stage, it can be amplified and projected to an audience. If the sound from e.g. a front loudspeaker is delayed in the above mentioned range and does not exceed 10 dB amplification, the image still appears to come from the performer. This works also for sound enhancement for distant locations.

2.3 Geometrical acoustics

The principle of geometrical acoustics is often used to predict a room's properties before building it. This is enabled by computer modeling.

Geometrical acoustics is based on a well know principle that was defined by Fermat (1601-1665): the sound propagates always on the fastest way from to receiver. In rooms, the medium air is homogenous and hence has the same propagation speed. This means that the fastest way is also the shortest way [3]. This corresponds to a straight line between source and receiver.

The basic principle of geometrical acoustics is to decompose the sound energy from the source into straight sound rays that propagate in all directions.

When these sound rays hit a reflective surface, they spread into new sound rays that can propagate back to the source. This is called reflection [3].

The process of reflection follows similar laws as know from optics [5]. When reflected the ray stays in the plane from the incident ray and is reflected half by the normal to the wall. The incident angle corresponds to the outgoing angle which is characterized as a specular reflection. Consequently, a ray that is reflected in a corner (double reflection) travels back in the same direction as the incident ray.

This gives rise to the principle of image sources. The reflected ray is thought of as coming from an image source which is located mirrored to the original source (or behind the reflective boundary). Once knowing the image source, this boundary can be omitted in the model and is replaced by the image source.

Image sources can be applied for first order reflections but also for higher order reflections which are image sources of the previous image source. A rectangular room can in this way be replaced by the following model:

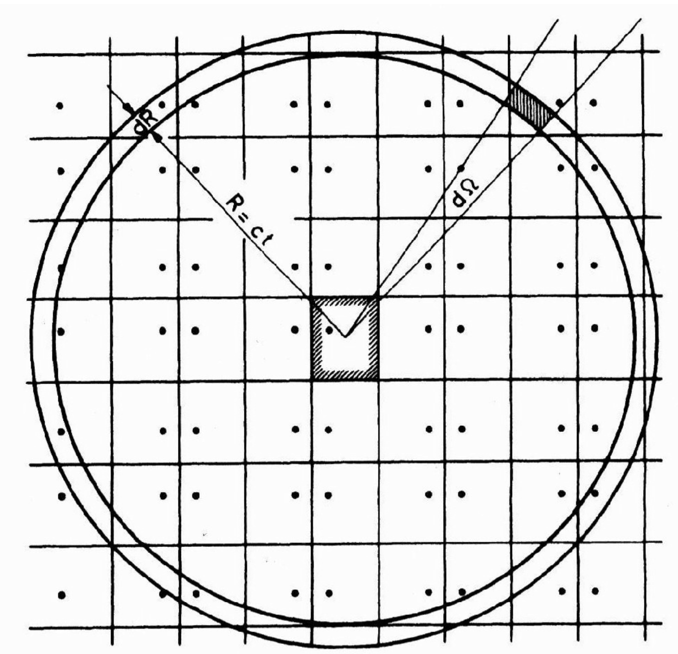


Figure 2: Image sources of a rectangular room [5]

Usually, a boundary is not purely reflective. A part of energy that strikes a boundary is absorbed. Absorption corresponds to an energy loss that is transformed into heat in most cases. This fraction of energy which is not reflected is specified by the absorption coefficient. The absorption coefficient usually depends on the angle of incidence and on the frequencies.

All sound rays that propagate in a room will multiply reflect on room boundaries until they hit a purely absorbing surface. Even if there is no purely absorbing surface in a room, the carried energy becomes vanishingly small as the rays loose their energy is gradually on the path.

All these principles are used to calculate the propagation of sound in a room. All rays travel different distances so they will arrive at the receiver position with different arrival time and strength. In order to obtain, the signal at the receiver position the sound pressures of all contributions are added. Interference is not considered in room acoustics. Thus the rays are incoherent to each other.

If the absorption coefficient of a boundary is frequency independent, the received signal s'(t) is the superposition of infinitely many image sources with their particular strength A_n and delayed by their particular travelling time t_n:

(1) $$s'(t) = \sum_n A_n s(t - t_n)$$

The impulse response serves as a tool to study reflections and reverberation in a room. It is the result of the time the sound needs to travel from the sound source to the room's boundaries and finally to the receiver [1]. It is then defined as [5]:

(2) $$g(t) = \sum_n A_n \delta(t - t_n)$$

In reality, the Dirac impulse will be changed slightly when reflected from a boundary and s not the exact copy of the original impulse. The Fourier transform of this signal is the reflection factor R.

Finally, we should respect that reflections are not only specularly reflected from boundaries. Diffusive boundaries split the sound rays into several new sound rays with randomly new directions that are independent of the incident angle. This results in a more uniform sound energy distribution in the room.

The model of geometrical acoustics is approximated by the following aspects [1], [5]:
- sources and receivers are small and their position can be interchanged
- all surfaces are plane and rigid and have dimensions that are much larger than the wavelength
- sources are unaffected by their surroundings
- source signals are assumed to be a short pulse
- only partially diffuse reflections can be achieved
- diffraction and interference are not considered.

In the past decades, the Schröder frequency is defined as the lower limit where geometrical acoustics is applicable [6]. In 1954 Schröder considered this frequency to be a limit between the lower frequencies with little modal overlap and the higher frequencies with strong modal overlap. The Schröder frequency is defined as:

$$(3) \quad f_s = 2000\sqrt{\frac{T}{V}}$$

The limitations to the model of geometrical acoustics will cause that real room measurements will show deviations from the calculations. Nevertheless, geometrical acoustics is a powerful tool in analyzing reflections in a sufficient way [1].

2.4 Basic principles of studio and control rooms

Studio and control rooms are used to record music or speech and bring it to an end customer. This implies that the design of the rooms needs to find a fine balance between enabling monitoring on a high quality level but also representing the sound perception in a domestic living room.

The first studio and control room raise with the invention of the radio that brought music to everyone's home. Local rooms were used which resulted in complaints that it was heard to listen to the actual content because of background noise. Hence, the performers were isolated in soundproof rooms to omit disturbances.

Studio and control rooms developed much in the beginning of the 20th century. It was mainly professionals that recorded for music and film with a high degree of sophistication [7].

Often, the control room was a smaller room adjacent to the studio with no special treatment [8].
The appearance of studio and control rooms boomed with the introduction of stereo recordings in the mid fifties. This new recording technique made the room very important as you need symmetry along the median plan to keep the stereo picture stable.

A new generation of studio and control rooms was needed.

One of the major designers of that time was Tom Hidley [8]. According to Voetmann, Hidley has expressed his thoughts in an interview where he remembers his time working as a sound engineer in Hollywood. Between sessions, the crew was taking breaks on the roof of the building where they had installed a set of professional monitor loudspeakers and listened to music. For Hidley, these loudspeakers were the best sounding loudspeakers he heard, playing in an open hemisphere. His design motivation in studio and control rooms was to recreate this sound.

In reality, it is impossible to realize this kind of semi-anechoic room with zero reverberation time and only one reflecting surface due to size limitations. Also, the sound perception would be unrepresentative for people's living rooms which is the main customer.

Hidley realized his studio and control rooms with the following features instead [8]:
- high degree of symmetry along a median plane
- no reflections from the back wall or ceiling
- monitor loudspeakers built into and flush mount with the front wall
- short reverberation time of control room down to low frequencies

Early designs of Hidley included a reflective element that hung above the mixing console. These early reflections were recommended by the designer but never explained. In later designs, this detail was omitted and instead the front part of the room was mostly absorptive.

He adapted to the up-come of a new type of control room: the *LEDE* . Chips and Don Davis introduced the Live End Dead End in 1979. In contradiction to the design of previous control rooms, the front wall should be as non-reflective as possible. In this way, the listener should only here the direct sound from the loudspeaker.

As a too dry room was not desirable, reflections were needed but should not be specular as they could cause coloration. Chips and Don Davis concluded that reflections should originate from the back wall and be diffuse.

The concept of the LEDE required a minimum size of the room so that there is a sufficient delay of the arrival time of early reflections at the listener which is related to the Haas effect 2.2.

The principle of LEDE was further extended and resulted in the design of control rooms with a *reflection free zone* .

These control rooms are purely geometrically designed. The front wall and ceiling was designed in a way that reflections pass around the mixing area. The listener would only perceive the direct sound from the loudspeakers. This approach is only valid for high frequencies which works for stereo recording as it is mainly related to a frequency range between 500 Hz to 5 kHz.

Studio technicians discussed an important problem: the recording on a vinyl, tape or other media that was passed between technicians for further editing sounded differently depending on the control room they were sitting having similar design concept. The room was leaving a foot print on the sound perception of the recording.

Hence, a new concept of control rooms raised: the *Non-environment control room.* This control room was supposed to be a neutral room where you listen to the pure sound coming from the loudspeakers. All room boundaries apart from the front wall and the floor were made nearly totally sound absorbing.
In this way, the sonic characteristics of recordings was preserved better when taking it from one non-environment to the other.
However, research shows that people need real rooms and experience discomfort in dead rooms.

In the last decades, recording material with good quality became available for everyone which gave rise to small domestic studios [7]. Much recording is now software based and the use of headphones for example reduces the importance of the room.

3 Method

As presented in the introduction, one aim of the thesis is to compare measurement and calculation of different studios.

Firstly, the chosen control and studio rooms are presented and described. The second part describes the measurement procedure and the third part focuses on the calculation description.
The parameters that are analyzed in the thesis are defined in the last part.

3.1 Rooms under study

On April 3rd 2013, I visited the Kanalhuset which contains Sveriges Radio och SVT together with Mendel Kleiner and Jan-Inge Gustavsson.

In agreement with both, we chose five studio and control rooms in total that seemed most interesting. Some studios were chosen because sound technicians working in them are satisfied and some because they are disliked.

These five rooms consists of two control rooms (category I) and three combined studio and control rooms for broadcast purposes. Two of the latter can be used in three ways (category II): as a control room, as a studio room or as a studio room where the program presenter is handling the broadcast alone. The last room is a studio room where the program presenter controls the broadcast alone (category III).

The following table lists the five rooms and their usage.

Room	Special property	Category
Studio 12	LEDE	I
Studio LLB 15	Surround sound TV	I
Studio 42	-	II
Studio 32	-	II
Studio 31	-	III

Table 1: Rooms under study

The first two control rooms were chosen because of their special acoustic design. Studio 42 and 32 are interesting because of their multiple use. Studio 31 was chosen because we were told that the sound technicians are not satisfied with the acoustics in this studio.

In the following subsections, the studios are described more detailed.

3.1.1 Studio 12 - LEDE

Studio 12 is a LEDE - Live End Dead End control room. The basic principles of a LEDE are described in subsection 2.4.

The following figure shows a panoramic view of Studio 12.

Figure 3: panoramic view Studio 12 - LEDE. Photo: Marco Verdi [12].

As characteristic for a LEDE, Studio 12 has a front part which is mostly absorptive and a back part which is mainly diffusing.

Absorption is provided by Ecophon Akusto on top of 45 mm mineral wool on walls and Ecophon Master alpha 40 mm on ceiling.
Diffusion is enabled by diffuser AD40, Svanå miljöteknik, which provides lateral diffusion in the room. This diffuser is diffusing in the frequency range 1 - 16 kHz.
A quite big part of the back wall i covered by wooden panels which are Helmholtz resonators tuned for max 160 Hz.

The floor is made of wood.

The room includes a big tilted window and two smaller windows which are tilted likewise.

3.1.2 Studio LLB 15 - Surround sound TV

Studio LLB 15 is used as a control room for surround sound in TV productions. The room has a special shape and treatment of the back wall.

The following figure shows a panoramic view of Studio LLB 15.

Figure 4: panoramic view Studio LLB 15 - Surround sound TV. Photo: Marco Verdi [12].

Studio LLB 15 borrows some characteristics of a LEDE. The front walls are absorptive, the ceiling above the first mixing table is absorptive as well. Walls around the back loudspeakers are completely clothed with Ecophon Wall Panel 40 mm on 45 mm mineral wool.

Diffusers of type AD 40, Svanå miljöteknik, are placed above the doors. The back side walls are covered by Diffusers of type AD 40, likewise the tilted ceiling in the back of the room.

The most special characteristic of this room is the back wall which is covered with a mathematical QRD diffuser (see subsection from Svanå miljöteknik called Golden Horn. This diffuser is diffusing in the frequency range 800 Hz - 16 kHz.
The property of such a mathematical diffuser is to scatter energy randomly. The cavities have different depth which alternates according to a mathematical sequence. In this way, the room is provided with a very smooth reverberation.

Studio LLB 15 has a wooden floor.

The use of Helmholtz resonators can be expected but information is not provided.

3.1.3 Studio 42

Studio 42 ca be used in three ways (see table 1).

The following figure shows a panoramic view of Studio 42.

Figure 5: panoramic view Studio 42. Photo: Marco Verdi [12].

The room has several windows which are surrounded by Ecophon Wall Panel 40 mm on 45 mm mineral wool. The three biggest windows are tilted.
A diffuser of type AD 40 is placed between the two smaller windows and in the back of the mixing table (to the right of one tilted window).

The upper 0.6 m are covered with Ecophon Wall Panel 40 mm on 45 mm mineral wool above windows and Helmholtz resonators (cite Westbrandt) above the remaining elements.

Studio 42 has a carpet on the floor.

3.1.4 Studio 32

As the previous studio, Studio 32 ca be used in three ways (see table 1).

The following figure shows a panoramic view of Studio 32.

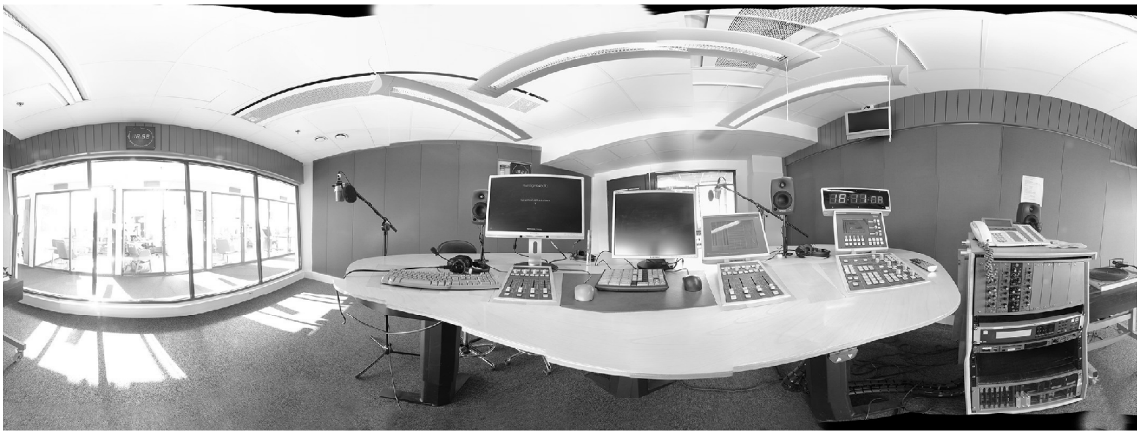


Figure 6: panoramic view Studio 32. Photo: Marco Verdi [12].

This studio has two big glass walls. The windows next to the glass door are not tilted. The three big windows across are tilted.

Both the left and right wall are covered with Ecophon Wall Panel 40 mm on 45 mm mineral wool.
Helmholtz resonators are probably installed above the left wall and the three big windows but concrete information is not available.

The ceiling is straight and 30 cm lower in the entry part. The material used for the ceiling is Ecophon Master alpha 40 mm.
The floor is covered with a carpet.

3.1.5 Studio 31

Studio 31 is a studio room where the program presenter controls the broadcast alone.

The following figure shows a panoramic view of Studio 31.

Figure 7: panoramic view Studio 31. Photo: Marco Verdi [12].

Studio 31 includes big window areas. It has a glassed door and three big window towards the open office, a glass facade and three windows towards the corridor. Approximately 55 % of the walls area is glass.

The majority remaining part of walls is covered by Ecophon Wall Panel 40 mm on 45 mm mineral wool.

Helmholtz resonators are probably installed above the windows next to the door and above the back wall. Again, no information is provided at this state.

The ceiling is straight and 30 cm lower in the entry part. The material used for the ceiling is Ecophon Master alpha 40 mm.

The floor is covered with a carpet.

3.2 Measurement

3.2.1 Measurement equipment and setup

The following equipment has been used during the measurements:

1	Laptop HP with Easera software
2	Sound interface Lexicon Omega
3	Loudspeaker Dynamic Acoustics BM 15 A in studio 12 - LEDE
	Loudspeaker Genelec 1038 A in surround studio
	Loudspeaker JBL Eon 10 G2
4	Measurement microphone Brüel & Kjaer
5	Power supplier Brüel & Kjaer 2804

Table 2: Measurement equipment

The following figure shows the measurement setup that was used in the studio.

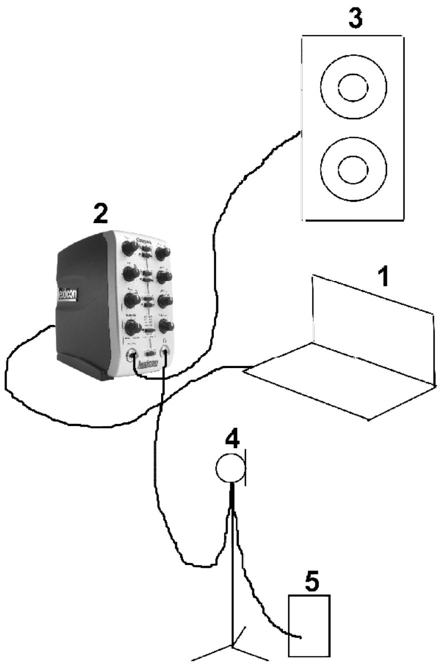


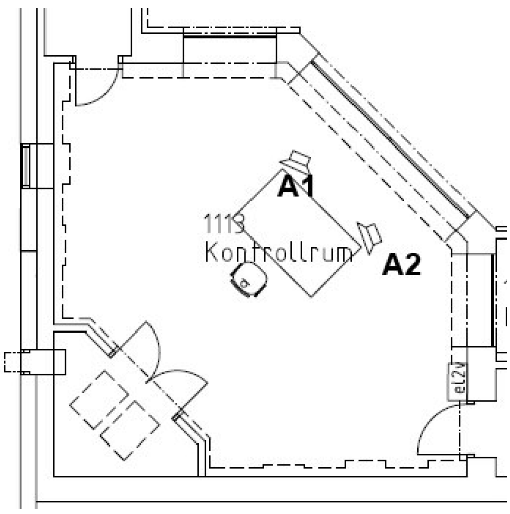
Figure 8: Measurement setup

The measurement signal used for the measurements of impulse responses in the five studio and control rooms was a weighted sweep over 10 averages. The background noise was very low in the studios. The signal to noise ratio has been adapted for each studio individually in order to reach SNR $\geq$ 40 dB.

3.2.2 Loudspeaker and microphone positions

The following figures show the loudspeaker and microphone positions in the five studio and control rooms. The microphone position is always placed at the listener position at the listeners ear height. This means 1.2 m for seating position and 1.6 m for standing position.

In studio 12 (LEDE) and the surround studio, I used the monitors for the measurement. For the other studios, the loudspeaker was placed on the floor and angled towards the listening position.



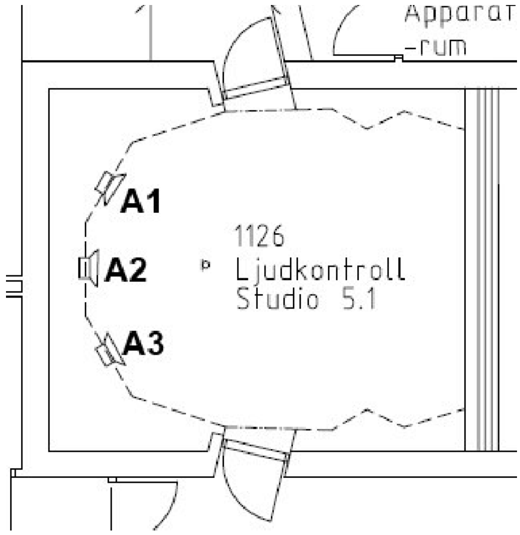


Figure 9: Microphone and loudspeaker positions in studio 12 - LEDE (left) and surround studio (right). Original drawing by Arkitekterna Krook & Tjäder AB Göteborg

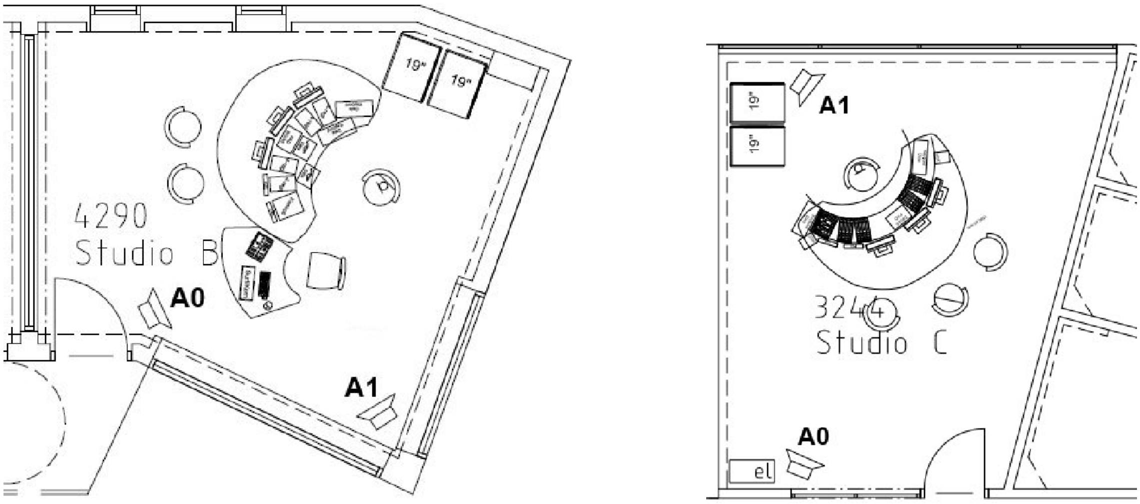


Figure 10: Microphone and loudspeaker positions in studio 42 (left) and 32 (right). Original drawing by Arkitekterna Krook & Tjäder AB Göteborg

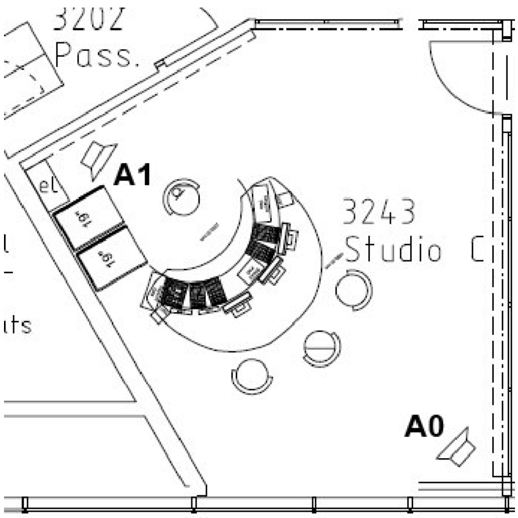


Figure 11: Microphone and loudspeaker positions in studio 31. Original drawing by Arkitekterna Krook & Tjäder AB Göteborg

3.3 Calculation

3.3.1 Basic principle

The calculation is performed with the room acoustical program CATT (acronym for Computer Aided Theater Technique).
This program uses geometrical acoustics (see subsection 2.3) which means ray tracing.

The software allows the user to specify absorption and scattering coefficients for different materials. These coefficients are stated as octave band values. In literature, absorption and diffusion coefficients are mostly stated from 125 Hz to 4 kHz.

The source is defined by its directivity information and frequency response.

The calculations in CATT are made for the octave bands 125 to 16 kHz. If no data is available for 8 and 16 kHz, theses values are extrapolated from 2 and 4 kHz.

CATT calculates the Schröder frequency (see subsection 2.3) in order to estimate from which octave band geometrical acoustics is valid. In the CATT manual [10] it is stated that this limit is estimated too low. Instead it is suggested that geometrical acoustics works well from a limit of $4f_s$ which matches experience from modeling small rooms. Additionally, he states that *for small rooms such as control rooms and studios typically only the upper octaves 1,2 and 4 kHz will be well predicted*

.
The calculation values for EDT, T20 and T30 from CATT are extracted for the pressure values (h). CATT gives also energy related calculation results (E). For receiver positions close to the source, the h- and E-based values will differ since EDT uses a straight line curve fit between 0 and -10 dB. But in reality the very early decay can be far from linear.

For the calculation of the rooms, I used algorithm 1 with a max split order of 2. This means that for 2 order reflections or lower, the diffuse and specular reflections are deterministic. For higher order reflections the reflections are determined randomly from the scattering coefficients [11]. Algorithm 2 and 3 use deterministic diffuse ray split-up also for higher orders. This means that each ray that hits a diffusing surface gives rise to many new rays. Algorithm 2 and 3 are mainly used for cases where there is risk for late reflections or flutter echoes, in outdoor situations or open rooms. As the focus of this Master thesis lies on the early reflections, I chose algorithm 1.

3.3.2 Room models

The following figures show the room models which are implemented in CATT. The same source and receiver positions as for the measurements are chosen.

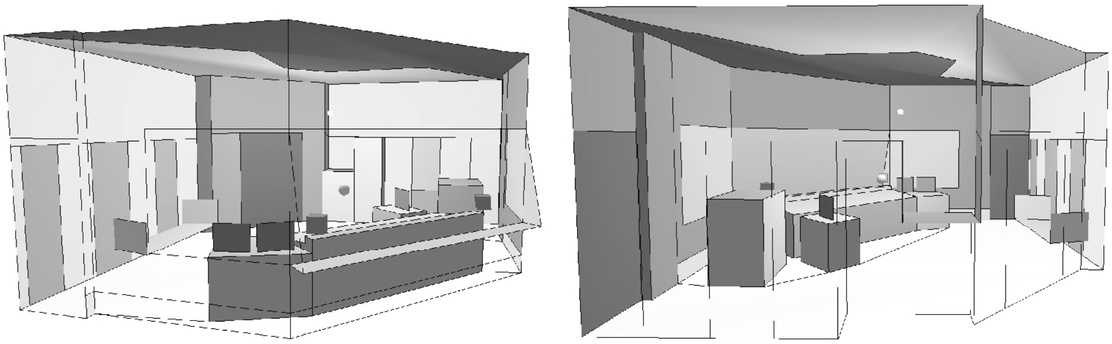


Figure 12: Calculation model in two views of studio 12 - LEDE

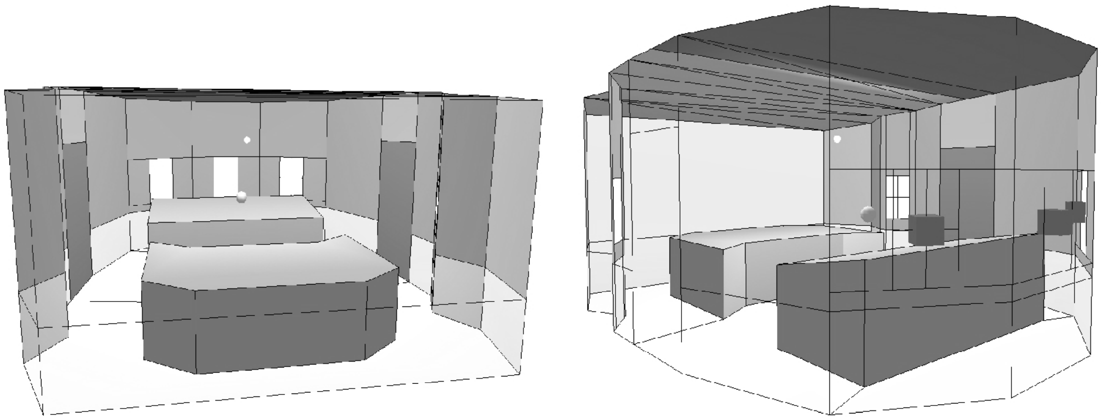


Figure 13: Calculation model in two views of surround studio

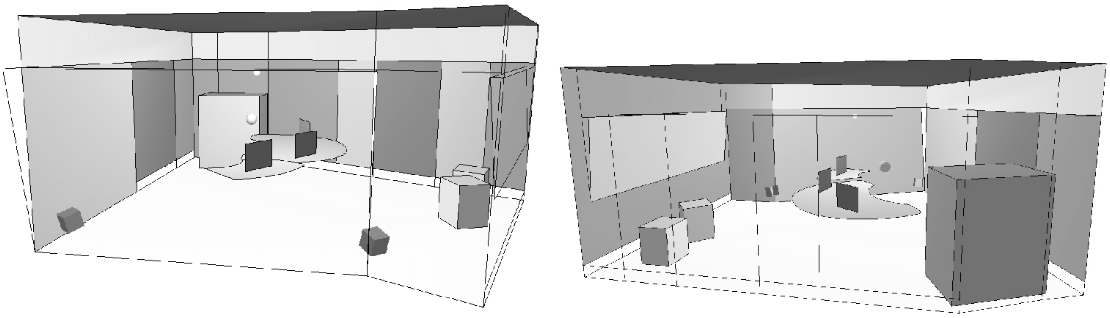


Figure 14: Calculation model in two views of studio 42

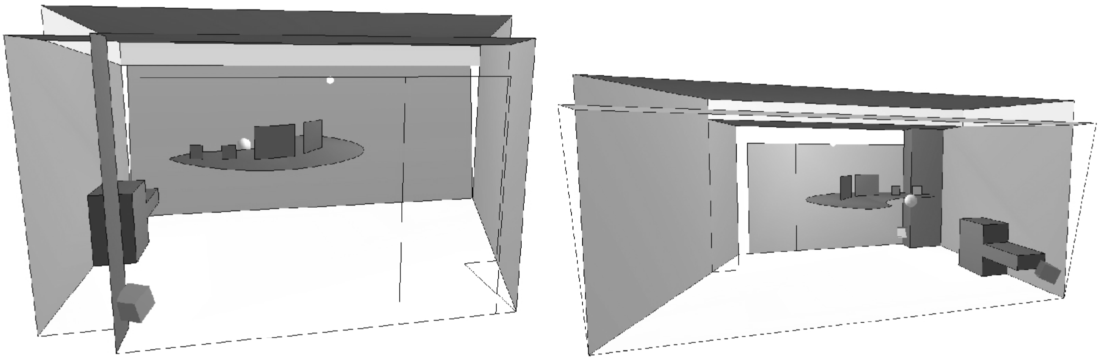


Figure 15: Calculation model in two views of studio 32

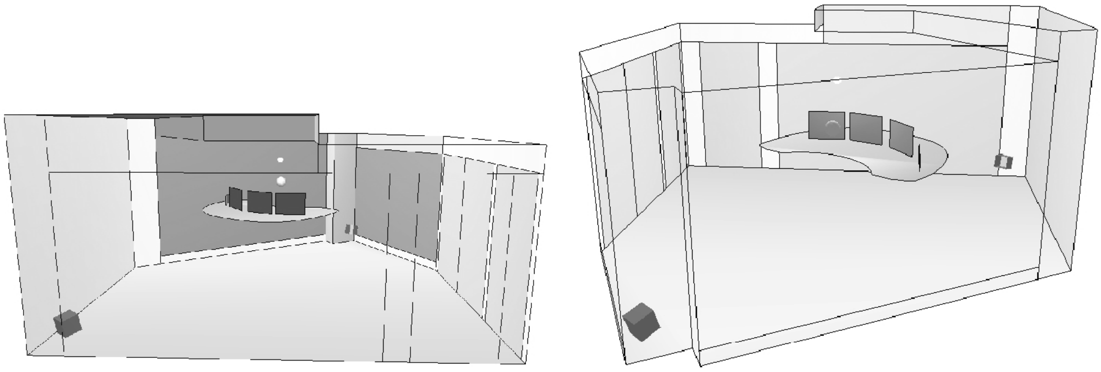


Figure 16: Calculation model in two views of studio 31

3.4 Analyzed parameters

3.4.1 Impulse response

The impulse response is the basis of all measures that are studied in the five studio and control rooms.
The IR of a system is defined as the output when a perfect pulse (delta function) is emitted. The impulse response is the Fourier transform of the transfer function [5].

$$(4) \quad g(t) = \int_{-\infty}^{\infty} p_\omega exp(i\omega t) d\omega$$

3.4.2 EDT

The reverberation time of a room is the time the sound needs to decay by 60 dB [9] and was introduced by Sabine.
The early decay time is extrapolated from a straight line drawn through 0 dB and -10 dB points The figure is then multiplied by six.

$$(5) \quad EDT = 60\text{dB} \frac{t_{-10} - t_0}{0\text{dB} - (-10\text{dB})}$$

The early part of reverberation curves is defined by the difference in level from the direct sound and the appearance in time of early reflections. Hence, EDT is varying much and is rather a local parameter.

3.4.3 T20

T20 is evaluated between -5 dB and -25 dB.

$$(6) \quad T20 = 60\text{dB} \frac{t_{25} - t_{-5}}{-5\text{dB} - (-25\text{dB})}$$

3.4.4 T30

T30 is evaluated between -5 dB and -35 dB.

$$(7) \quad T30 = 60\text{dB} \frac{t_{35} - t_{-5}}{-5\text{dB} - (-35\text{dB})}$$

3.4.5 Energy time curve

The Energy Time Curve ETC (Log-Squared) shows the energy decrease over time, where the individual samples are squared and then plotted on a logarithmic scale.

$$(8) \quad ETC = 10log_{10}g(t)^2$$

3.4.6 Cumulative energy curve

Kutruff [5] defines the cumulative energy curve as the following ratio:

$$(9) \quad CEC = \frac{\int_0^{\tau} |g(t)^n| \, tdt}{\int_0^{\tau} |g(t)^n| \, dt}$$

3.4.7 Frequency response

The frequency response of a continuous system is the Fourier transformation of the impulse response.

$$(10) \quad G(\omega) = \int_{-\infty}^{\infty} g(t) e^{i\omega t} dt$$

The frequency response is smoothed to 1/48 octave for the measurements.

4 Results

In this section, the results from measurements and calculations with CATT are presented for the five chosen studios. The results are always displayed as a comparison pair.
The results are described for each loudspeaker position in each room.
A deeper analysis is written in the Discussion section 5

4.1 Studio 12 - LEDE

In the LEDE (Studio 12) the measurement and calculation were performed with two monitors (see section 3). The results are presented with the parameters described in section 3.4.

4.1.1 EDT, T20 and T30

The following figures show the EDT, T20 and T30 of the two monitors.

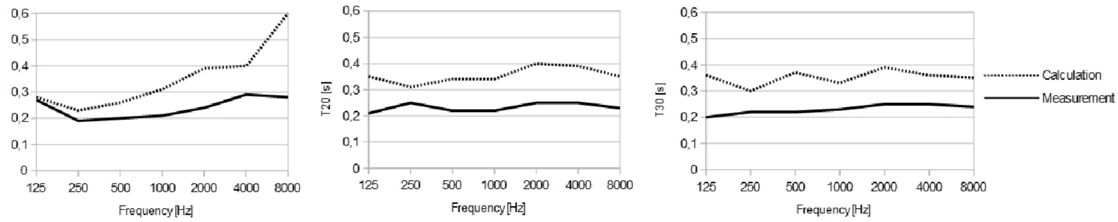


Figure 17: EDT, T20 and T30 [s] left monitor A1 in LEDE

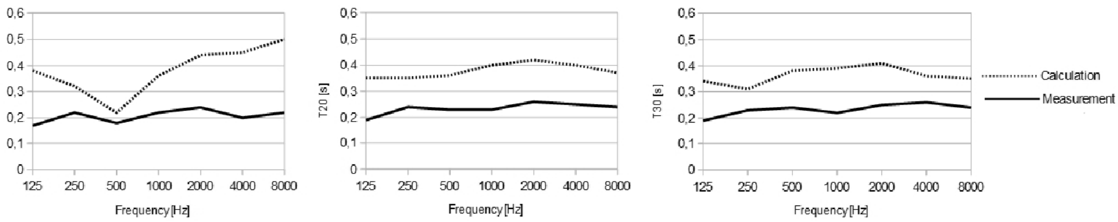


Figure 18: EDT, T20 and T30 [s] right monitor A2 in LEDE

When looking at the two figures, it can be noticed that the measured and calculated T20 and T30 values correspond better than the EDT.

The EDT differs considerably between measurement and calculation and between the two monitors.
For the left monitor A1, the curves correspond for octave bands 125 and 250 Hz. Thereafter the calculated EDT increases steeper compared to the likewise increasing measured EDT.
The right monitor does not give corresponding results in any frequency. Whereas the EDT by measurement is flat, the calculation gives an increasing slope.

As for T20 and T30,the calculated values are in average 0.1 s higher than the measured T20 and T30.
The measured curves for both monitors are flat in frequency. The calculated values for T20 and T30 differ slightly more in frequency. The octave band 250 Hz is shortest for both monitors and both T20 and T30, the octave band 2000 Hz is longest. The difference between the shortest and longest calculated reverberation time in respect with frequency is 0.1 s.

In general, T20 and T30 correspond well in pattern between measurement and calculation as all curves are pretty flat.

4.1.2 Impulse response

The following figures show the impulse response in mPa (measured) and relative 1 m on axis (calculated) for the first 20 ms after the direct sound. The figures are grouped as a comparison of measurement and calculation

The following figures show the impulse response for the first 20 ms with the left monitor in the LEDE control room.

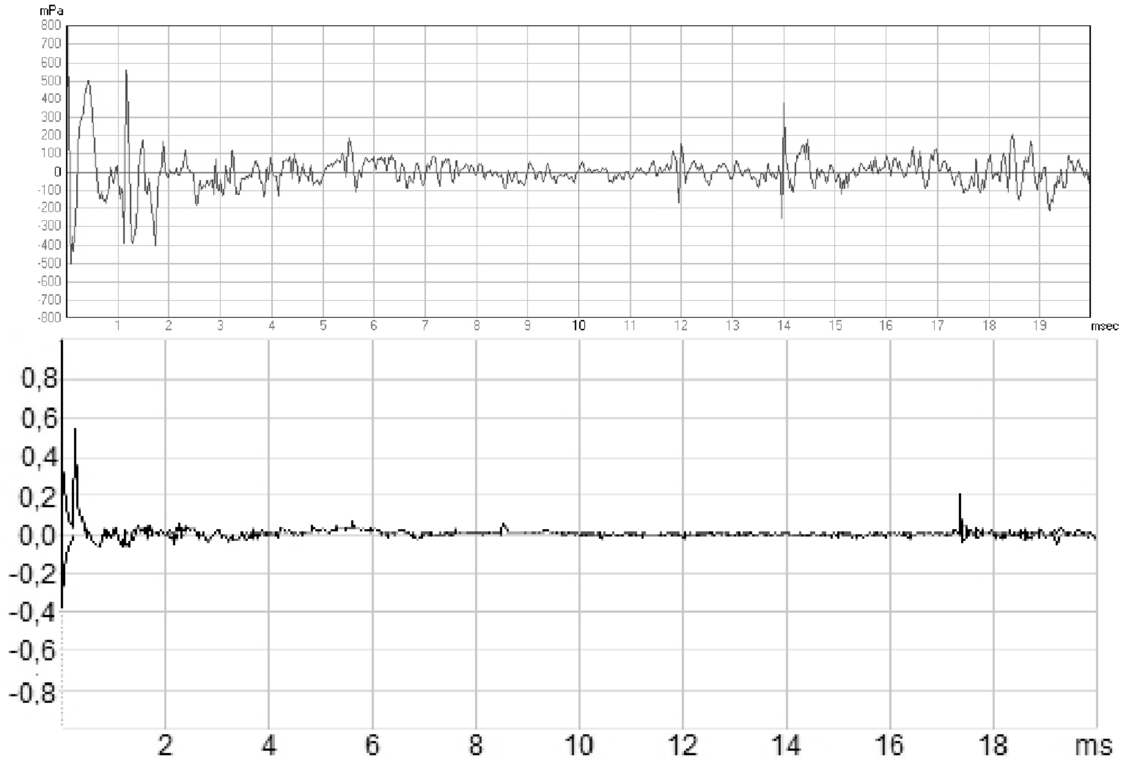


Figure 19: Impulse response for left monitor A1 in LEDE. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

For the measurement with the left monitor, there are two reflections after 0,5 ms and around 1 ms only. In the calculated IR, there is a very strong reflection after 0,5 ms.
The measured IR includes a less distinct reflection at around 5,5 ms and has a corresponding reflection in the calculated IR. The most distinct reflection appears at 14 ms in the measured IR.
The most distinct reflection in the calculated IR appears at around 17,5 ms instead.
It can be seen that the measured IR contains negative pressure fluctuations. The calculated IR has no distinct negative pressure fluctuation apart from the very first one.

Below, the impulse response from measurement and calculation are shown for the right monitor.

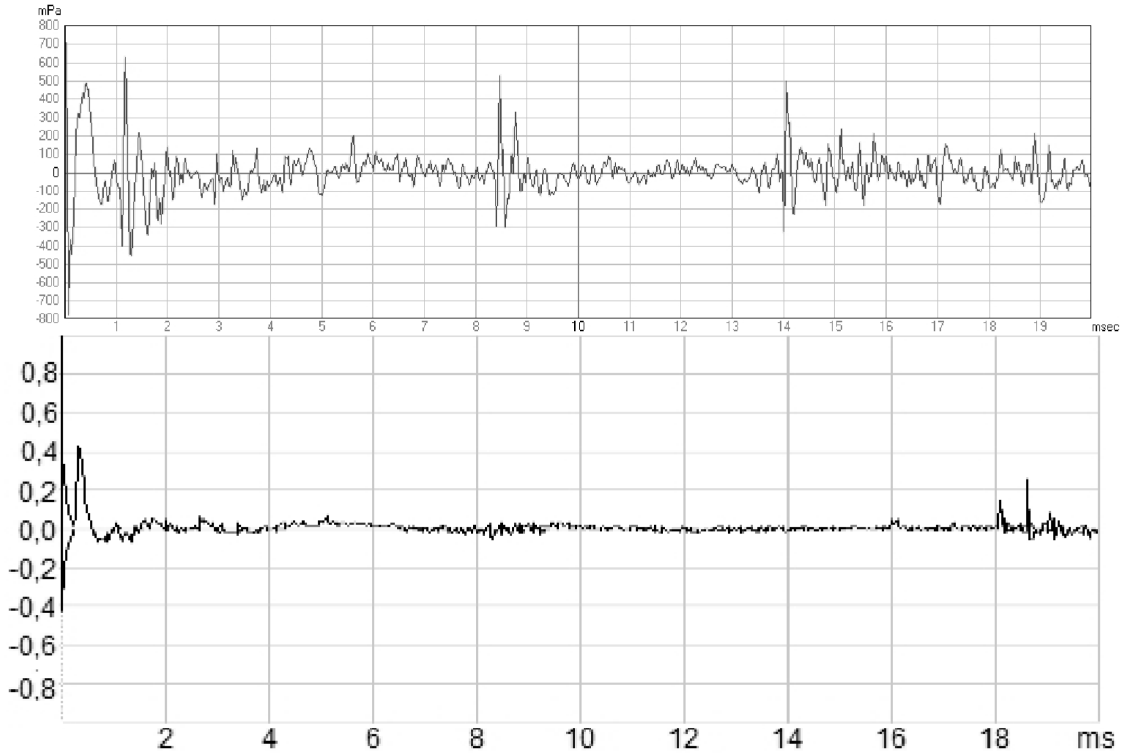


Figure 20: Impulse response for left monitor A2 in LEDE. Top graph presents the measured IR [mPa], the lower graph the calculated IR [Pa].

As for the other monitor there is a first reflection after 0.5 ms both for the measured and calculated IR. At 1 ms there is a reflection in the measured IR which can be recognized in the calculated IR but with much lower pressure value. The same counts for the two measured reflections around 8,5. As for the left monitor, the measurement with the right monitor contains a distinct reflection at 14 ms.

There are two distinct reflections after 18 ms in the calculated IR which have corresponding peaks in the measured IR.

As for the left monitor, the calculated IR has no concrete negative pressure fluctuations apart from the very first one.

4.1.3 Energy time curve

The figure below shows the energy time curve for the left monitor for the first 20 ms.

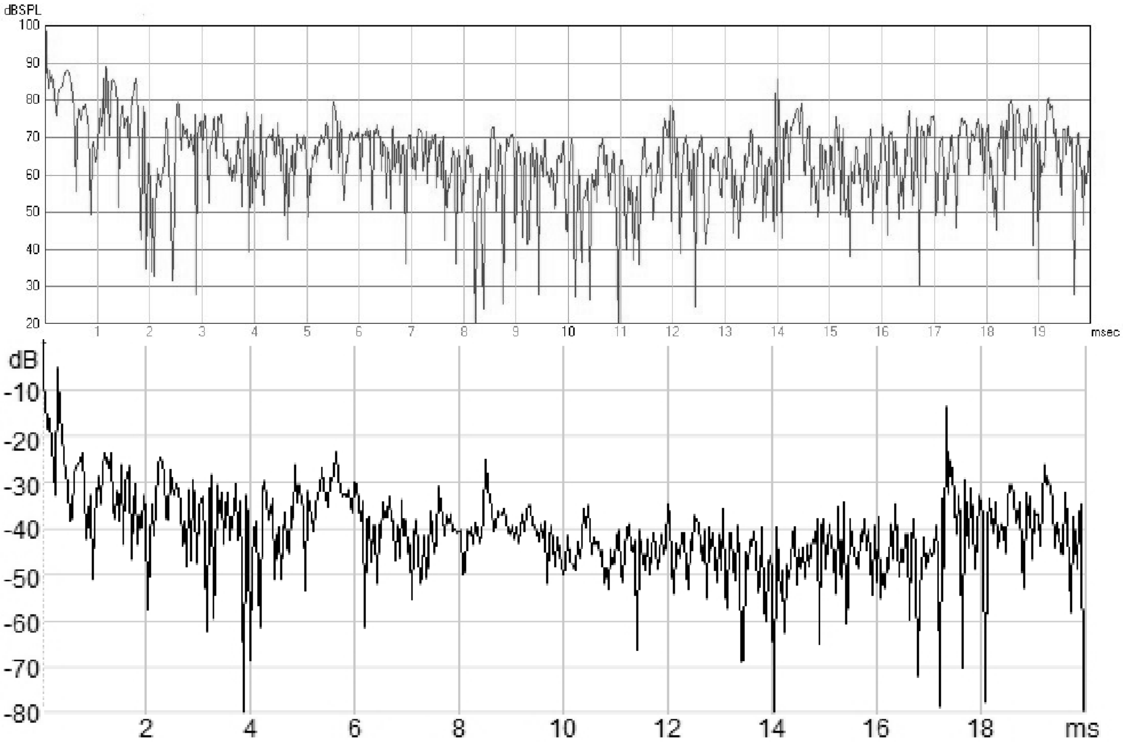


Figure 21: Energy time curve [dB] for left monitor A1 in LEDE. Top graph presents the measured ETC, the lower graph the calculated ETC.

The direct sound from the measurement takes a level of 98 dB. The calculated ETC is normalized to 1 m on axis.
The fist reflections up to 2 ms correspond well in time between measurement and calculation but have different levels. The measured reflections are around 10 dB lower than the direct sound whereas the calculated reflections are around 25 dB lower in level. An exception is the first reflection after 0.5 ms which is only 5 dB lower for the calculated ETC. For both measured and calculated ETC, there is a strong dip at 2 ms.
Following reflections correspond well in time and in relative level meaning that the pattern of the ETC is very similar. The calculated reflections are hereby around 5 dB lower than the measured ones.
The measured ETC contains distinct reflections at 5.5 ms, 12 ms and 14 ms. The strongest reflections in the calculated ETC occur at 5.5 ms, 8.5 ms and 17.5 ms. All these reflections have a corresponding reflection in the other ETC but the level differs.
The main pattern of the measured ETC is decreasing down to 11 ms and increases after that. Drawing a line through the reflection pattern indicates that the calculated reflections take levels that are 5 dB lower up to 11 ms and 10 dB lower for later reflections.

The following figure shows the energy time curve for the right monitor for the first 20 ms.

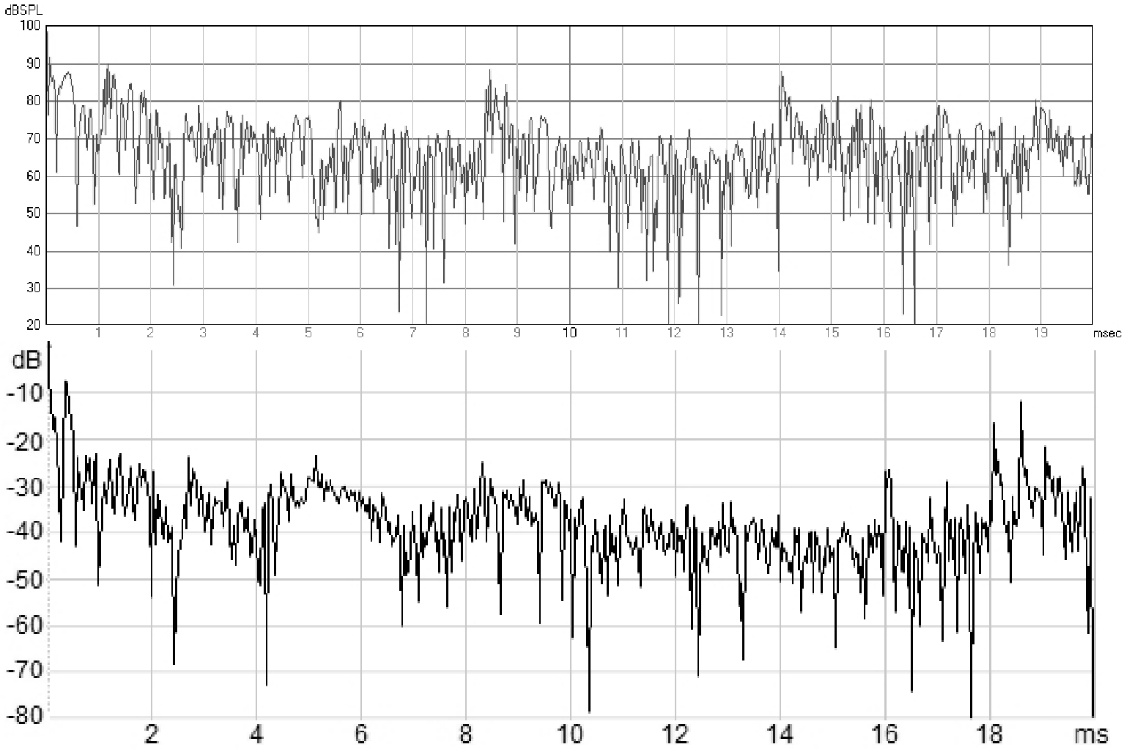


Figure 22: Energy time curve [dB] for right monitor A2 in LEDE. Top graph presents the measured ETC, the lower graph the calculated ETC.

The first reflection after 0,5 ms is 10 dB lower than the direct sound for the measurements and 9 dB lower for calculation. The reflection by measurement at around 1 ms is 9 dB lower than the direct sound.
The stronger reflections at 8,5 ms and 14 ms are measured around 10 dB lower than the direct sound. All other apparent reflections are at least 15 dB lower.
In the calculated ETC, there are some later reflections after 16 ms which are between 10-15 dB lower than the direct sound. All other reflections are at least 25 dB lower.

In general, the level pattern of the measured and calculated ETC corresponds well up to 13 ms.

4.1.4 Cumulative energy curve

The cumulative energy curve allows one to judge the importance of the reflection to the overall sound build-up in a room (see section 3.4).

The following figures show the cumulative energy curve for loudspeaker position A1 for the first 20 ms.

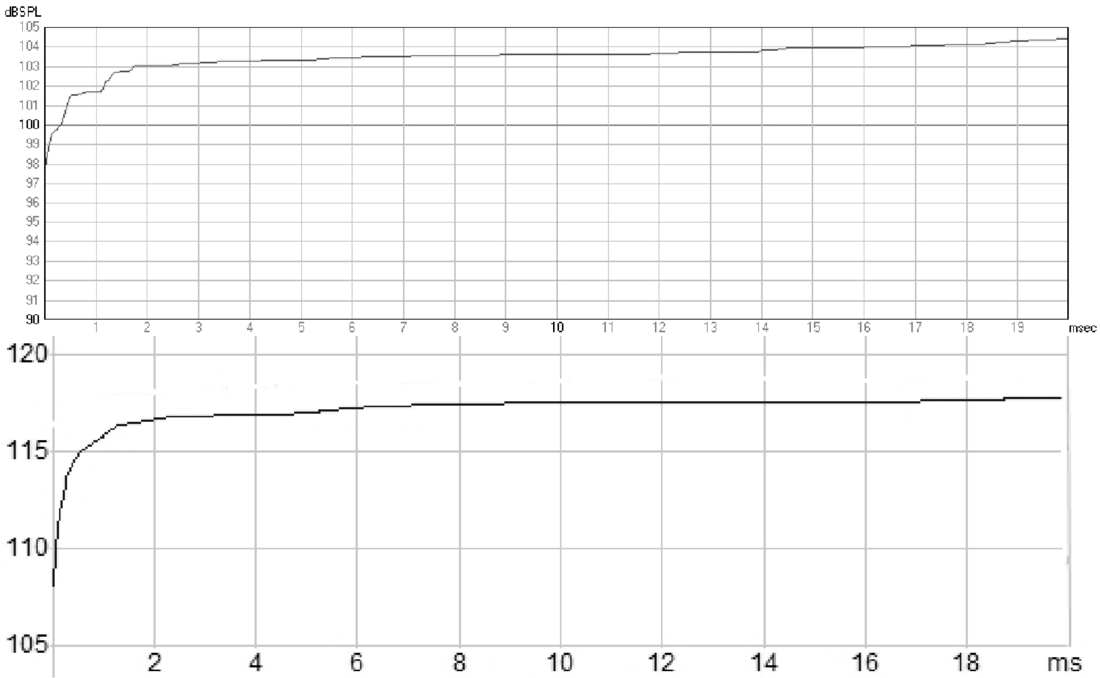


Figure 23: Cumulative energy curve [dB] for loudspeaker position A1 in LEDE. Top graph presents the measured CEC, the lower graph the calculated CEC.

The measured cumulative energy curve shows several reflections that contribute strongly to the sound build-up in the first 2 ms. The strongest reflection occurs at 0.5 ms which corresponds well to the information given in the energy time curve in figure 21. Later, there are no distinct reflections, only a minimal increase around 14 ms and 18 ms.

The calculated CEC shows a strong contribution to the sound build-up in the first millisecond. Otherwise there are no distinct reflections that contribute. A minimal increase can be seen around 5.5 ms.

Both the measured and calculated CEC increase linearly in a similar slope from 2 ms.

The following figures show the cumulative energy curve for loudspeaker position A2 for the first 20 ms.

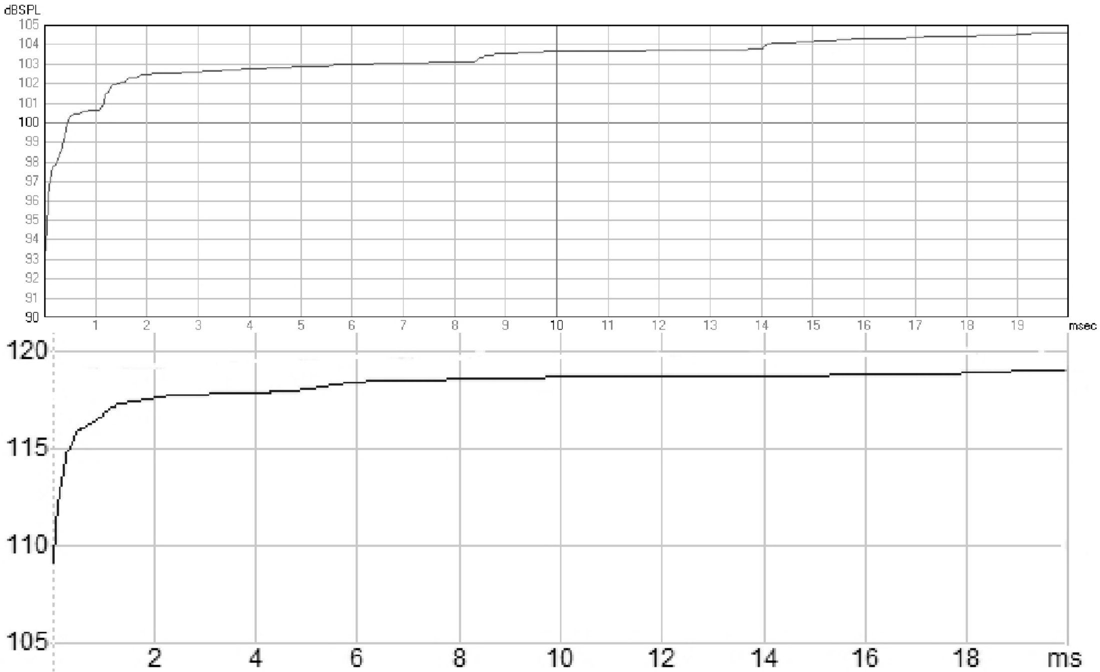


Figure 24: Cumulative energy curve [dB] for loudspeaker position A2 in LEDE. Top graph presents the measured CEC, the lower graph the calculated CEC.

The most dominant reflections in the measured CEC appear at 0.5 ms and 1 ms. At 8,5 ms and 14 ms much weaker reflections contribute to the sound build-up.

In the calculated CEC, the most dominant reflections appear in the first 0.5 ms. A reflection around 5.5 ms causes a slight increase in the cumulative energy curve.

The general increasing slope for measurement and calculation is very similar.

4.1.5 Frequency response

The following figure shows the measured and calculated frequency response on a logarithmic scale for left monitor A1.

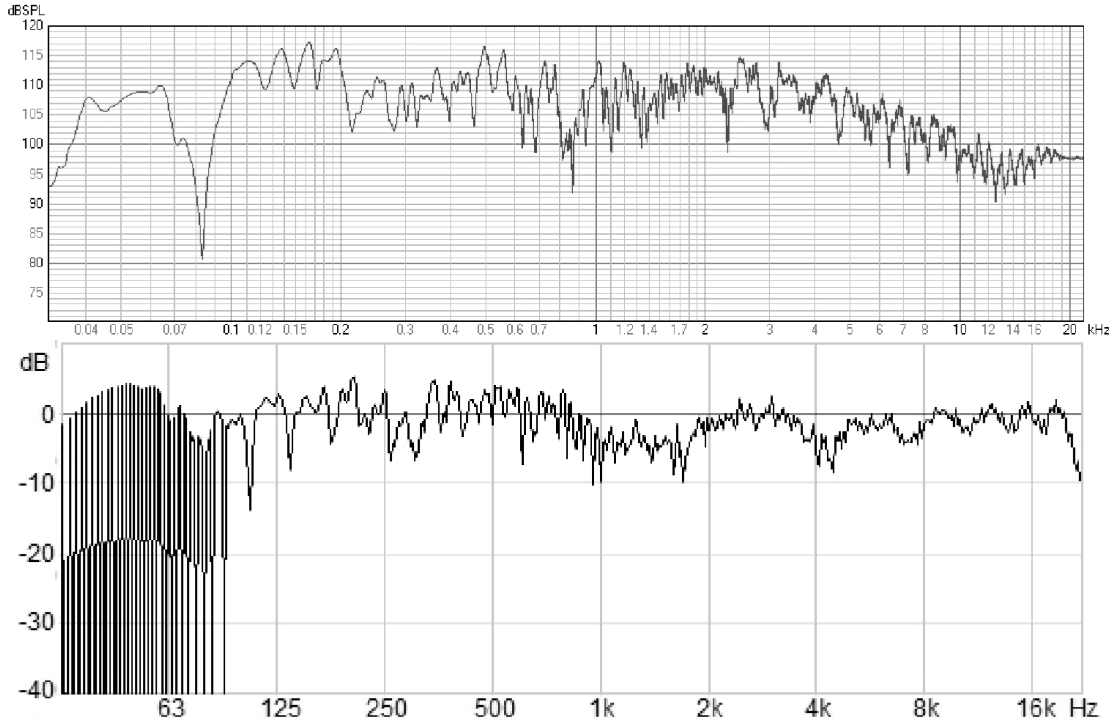


Figure 25: Frequency response [dB] for left monitor A1 in LEDE. Top graph presents the measured FR, the lower graph the calculated FR.

The frequency response measured with the left monitor A1 shows a very distinct interference pattern.
There is a strong dip at 80 Hz. The frequency response is quite flat between 100 Hz and 4 kHz. For higher frequencies, the slope is decreasing.

For the calculated frequency response, the results are strange up to 80 Hz. Again, a clear interference pattern can be seen. The frequency response is quite flat over the whole frequency range and only decreases steeply around 18 kHz.

The following figure shows the measured and calculated frequency response on a logarithmic scale for right monitor A2.

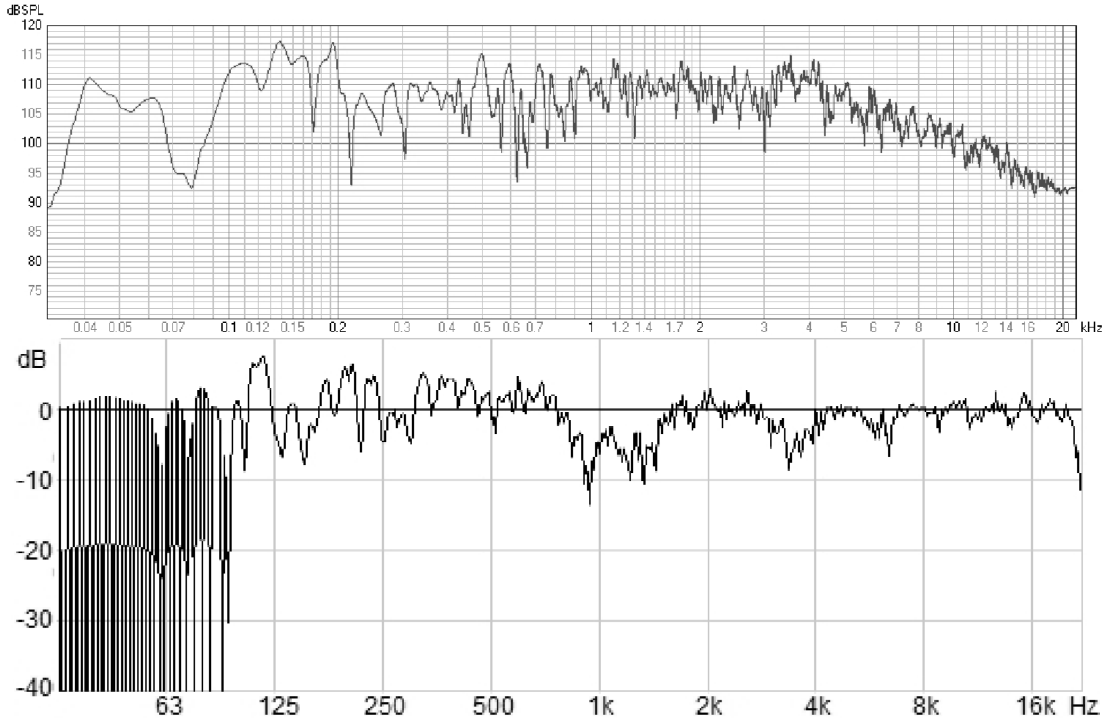


Figure 26: Frequency response [dB] for right monitor A2 in LEDE. Top graph presents the measured FR, the lower graph the calculated FR.

Similar to the left monitor, the frequency response of the right monitor is quite flat up to 4 kHz. There is a dip at 80 Hz. Again, this monitor shows an interference pattern. The slope decreases 4 kHz.

The calculated frequency response includes strange levels up to 80 Hz. Thereafter, the frequency response shows a clear interference pattern. The response is flat up to 18 kHz.

4.2 Surround studio

4.2.1 EDT, T20 and T30

The following figures show the EDT, T20 and T30 for monitors A1, A2 and A3.

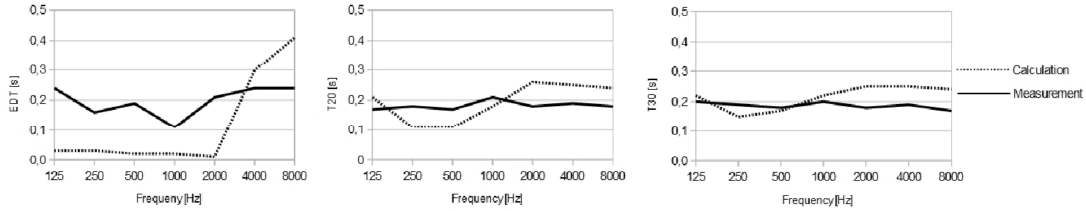


Figure 27: EDT, T20 and T30 [s] loudspeaker position A1 in surround studio.

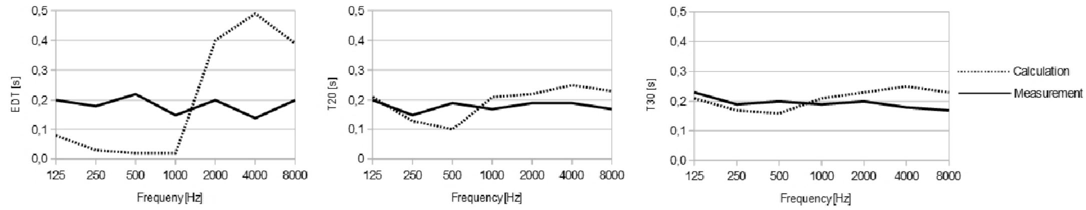


Figure 28: EDT, T20 and T30 [s] loudspeaker position A2 in surround studio.

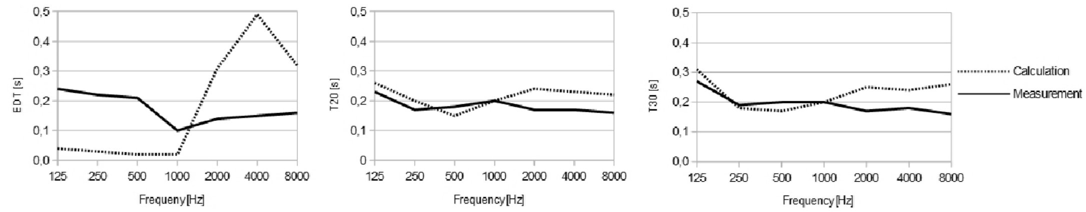


Figure 29: EDT, T20 and T30 [s] loudspeaker position A3 in surround studio.

Generally, the above figures show that there is no correspondence for EDT but good correspondence for T20 and T30 between measurement and calculation.

EDT differs much between the three monitors and is not as flat as T20 and T30.
EDT by calculation takes extremely low values up to 2 kHz for monitor A1 and up to 1 kHz for monitors A2 and A3. Thereafter, EDT increases with 0.4 s. For A1 it reaches its max at 8 kHz. For A2 and A3, the max is reached at 4 kHz and decreases for 8 kHz.

The measured T20 and T30 are flat for monitors A1 and A2 and differ slightly in frequency as a linear decreasing slope for monitor A3. The octave bands 125 Hz and 250 Hz have the tendency to take higher values for T30 compared to T20 for all monitors.

The calculation of the surround studio corresponds better with the measurement for T30 than for T20.
It underestimates the reverberation time T20 for the octave bands 250 Hz and 500 Hz for monitors A1 and A2. A3 on the other side shows good correspondence for the lower frequencies. This effect can also be seen for T30 but not as distinct.

Higher frequencies from 2 kHz and upwards are overestimated by calculation for T20 and T30 likewise.

4.2.2 Impulse response

The following figure shows the impulse response in mPa (measured) and relative 1 m on axis (calculated) for the first 20 ms after the direct sound. The graphs are grouped as a comparison of measurement and calculation.

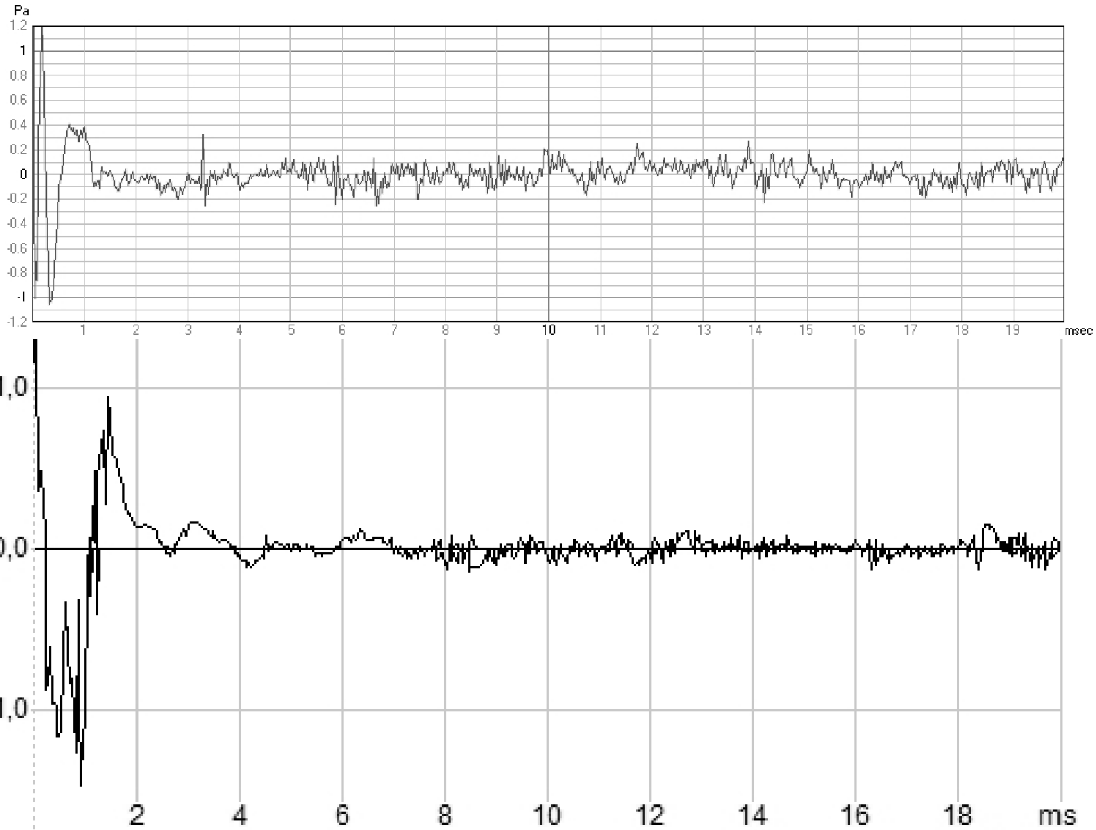


Figure 30: Impulse response for loudspeaker position A1 in surround studio. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

The impulse response for monitor A1 shows the same behavior for measurement and calculation. The direct sound is very strong followed by a very early reflection after 0.2 ms (this reflection is harder to see in the calculated IR as there is no negative contribution). This first reflection is followed by a dip at 0.5 ms. As for the measured IR, there is a series of reflections around 1 ms. The calculated IR has an agreeing peak which is shifted in time.
A third reflection appears at around 3 ms. No more distinct reflections can be seen later in the measured and calculated IR in this scale.

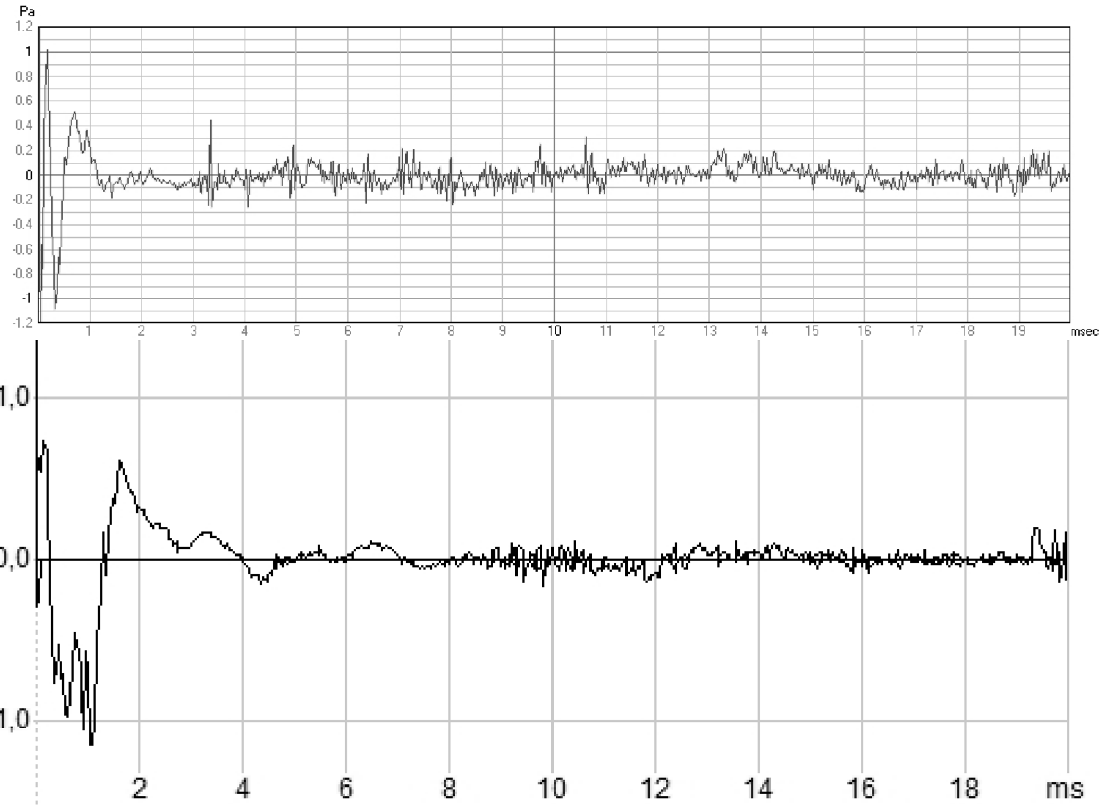


Figure 31: Impulse response for loudspeaker position A2 in surround studio. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

The measured and calculated IR are very similar to monitor A1. The first reflection agrees in time, the second peak is slightly shifted for the calculation.
The third reflection is measured at around 3 ms.
Later reflections occur after 19 ms in both measured and calculated IR.

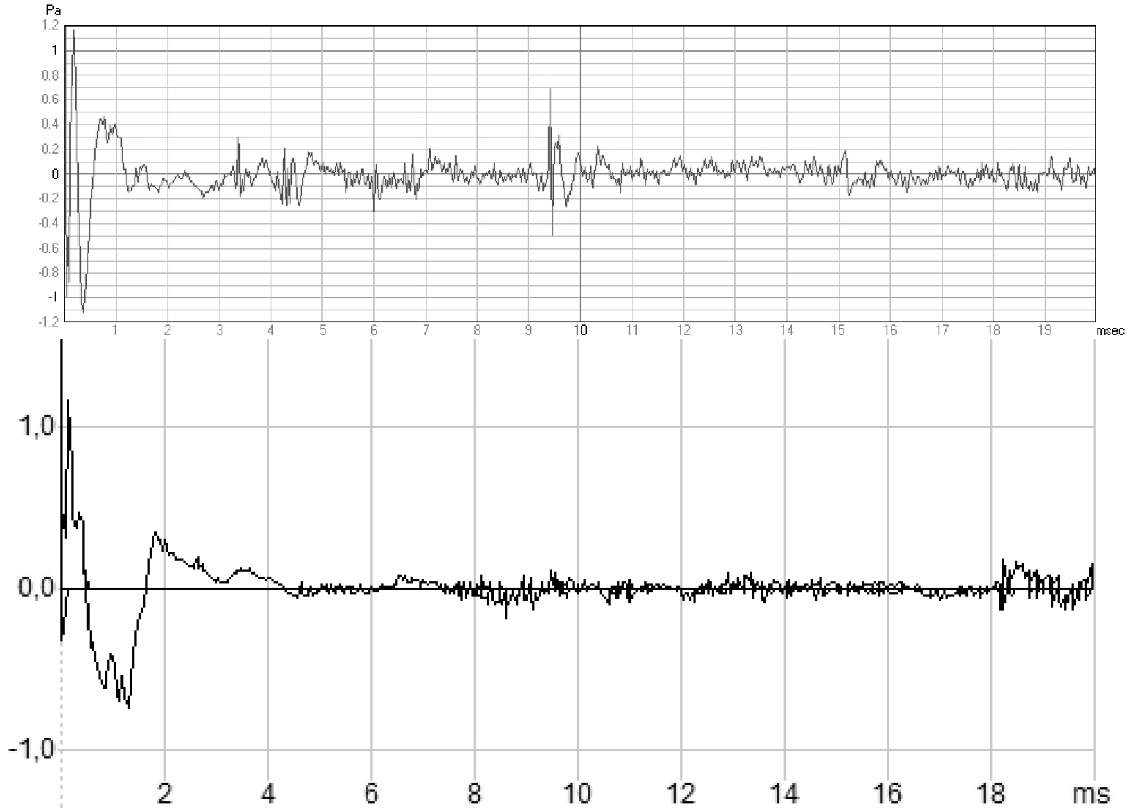


Figure 32: Impulse response for loudspeaker position A3 in surround studio. Top graph presents the measured IR [mPa], the lower graph the calculated IR [Pa].

Monitor A3 shows the same characteristics as the previous monitors A1 and A2.

Monitor A3 differs by a strong reflection at 9.5 ms that appears in the measured IR. There is no strong corresponding reflection in the calculated IR.

4.2.3 Energy time curve

The figure below shows the energy time curve for the monitor A1 for the first 20 ms.

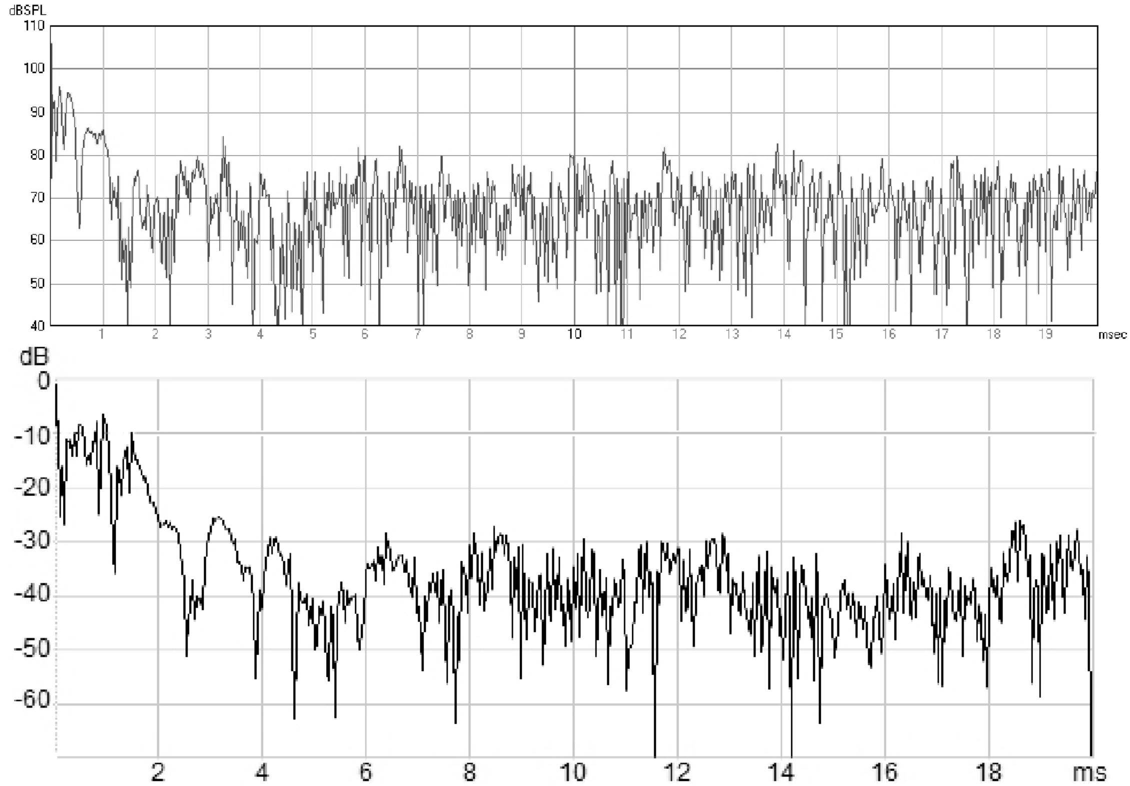


Figure 33: Energy time curve [dB] for loudspeaker position A1 in surround studio. Top graph presents the measured ETC, the lower graph the calculated ETC.

The measured ETC is decreasing in level down to 5 ms whereas the calculated one decreases down to 6 ms Looking at these two first time intervals, the calculated ETC is shifted by around 0.5 ms for all peaks and dips. This is harder to perceive for later reflections as they are not as distinct.

The first reflections up to 0.5 ms in the measured ETC and up to 1 ms in the calculated ETC, are 10 dB lower than the direct sound. All other measured reflections are around 25 dB lower, all other calculated reflections about 30 dB lower.

The curves are quite flat when drawing a trend line.

The figure below shows the energy time curve for the monitor A2 for the first 20 ms.

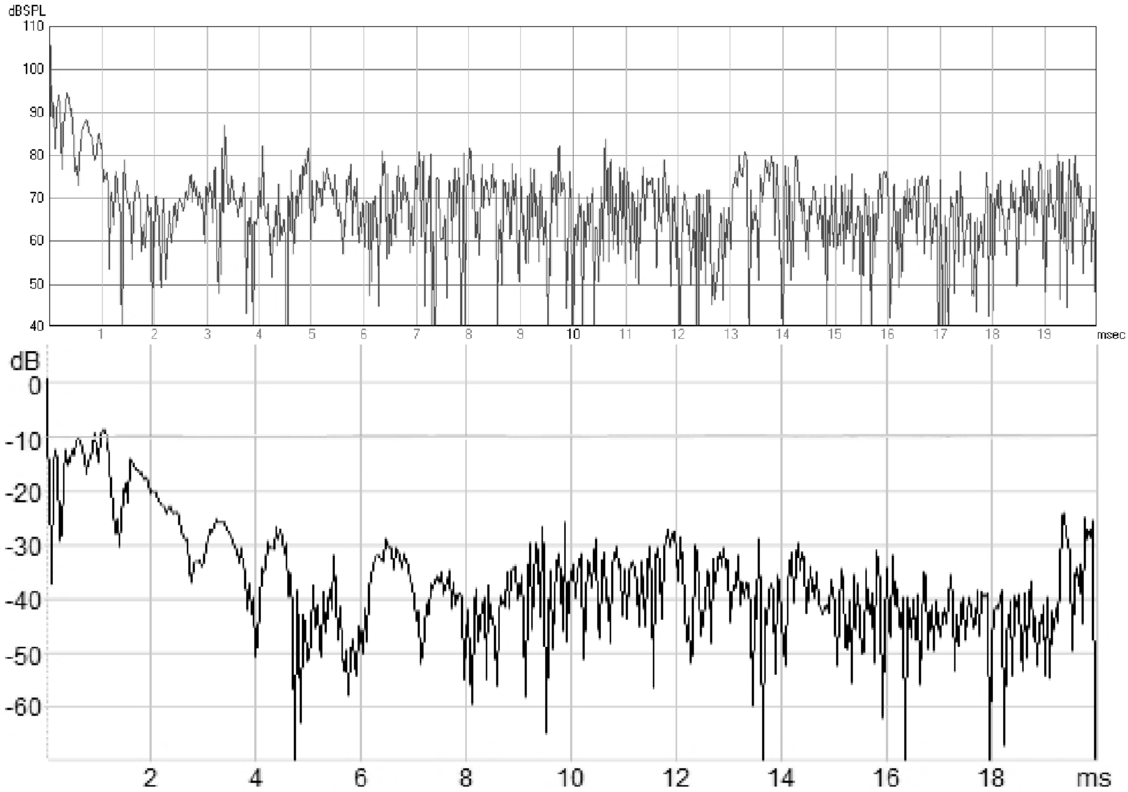


Figure 34: Energy time curve [dB] for loudspeaker position A2 in surround studio. Top graph presents the measured ETC, the lower graph the calculated ETC.

The same phenomena as for monitor A1 can be seen in the measured and calculated energy time curves above.
The peaks and dips are shifted by about 0.5 ms.

Again the first measured reflections are 10 dB lower than the direct sound. Reflections after 3.5ms are around 25 dB lower than the direct sound.
The first calculated reflections are also at least 10 dB lower. Reflections after 4 ms are around 30 dB lower than the direct sound.

There is a slight increase in level after 18.5 ms by measurement and after 19 ms by calculation.

The figure below shows the energy time curve for the monitor A3 for the first 20 ms.

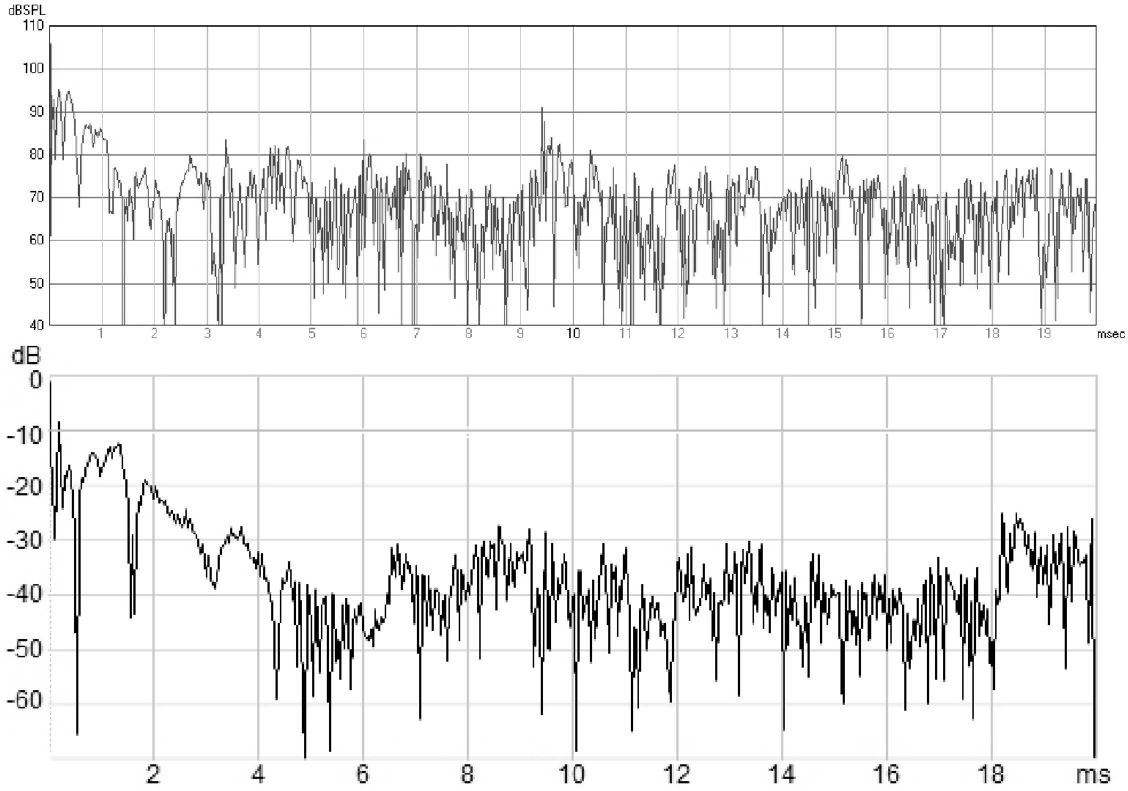


Figure 35: Energy time curve [dB] for loudspeaker position A3 in surround studio. Top graph presents the measured ETC, the lower graph the calculated ETC.

As previous monitors, the calculated ETC for monitor A3 is shifted by less than 0.5 ms compared to the measured ETC.
Again, the first reflections are around at least 10 dB lower than the direct sound for both measurement and calculation. Later reflections by measurement are around 25 dB lower. There is a stronger reflection at 9.5 ms that is only 15 dB lower than the direct sound. All other reflections in the calculated ETC are around 30 dB lower. An exception are reflections after 18 ms which are about 25 dB lower.

4.2.4 Cumulative energy curve

The following figures show the cumulative energy curve for monitor A1 for the first 20 ms.

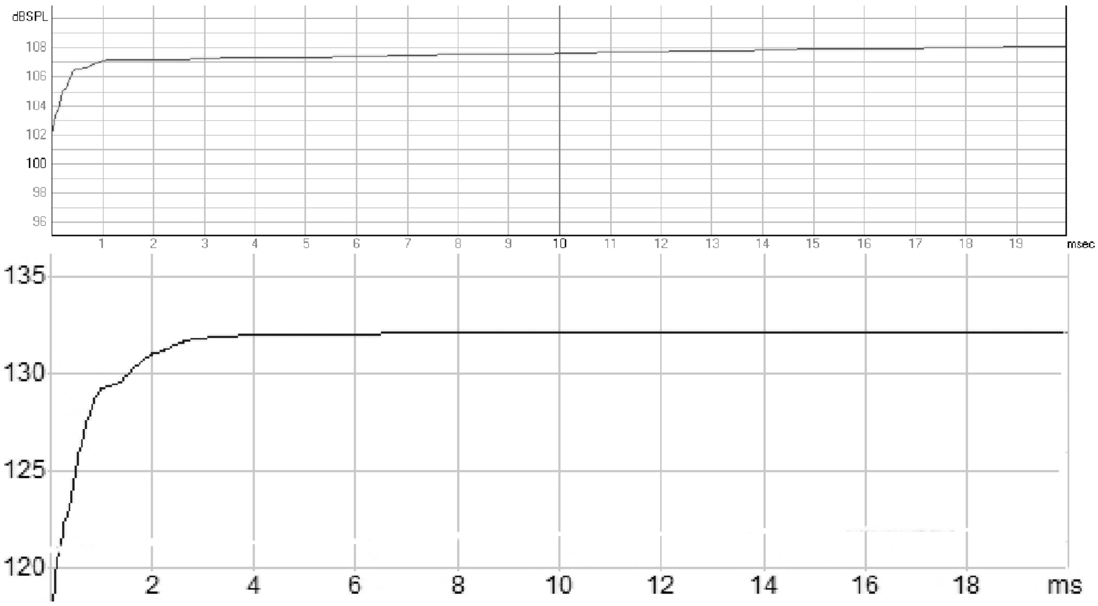


Figure 36: Cumulative energy curve [dB] for loudspeaker position A1 in surround studio. Top graph presents the measured CEC, the lower graph the calculated CEC.

The sound build-up in the surround room by measurement is faster than by calculation. The first reflections up to 1 ms contribute most to the sound build-up. Some later reflections are contributing slightly as the curve is increasing but it can not be seen distinctively.

For the calculated CEC, it is the first reflection after 0.2 ms and after 1 ms which contribute mostly to the sound build-up. Otherwise the sound is very constant and no reflections contribute later.

The total sound level in the room after 20 ms reaches 108 dB for measurement and 132 dB for calculation.

The following figures show the cumulative energy curve for monitor A2 for the first 20 ms.

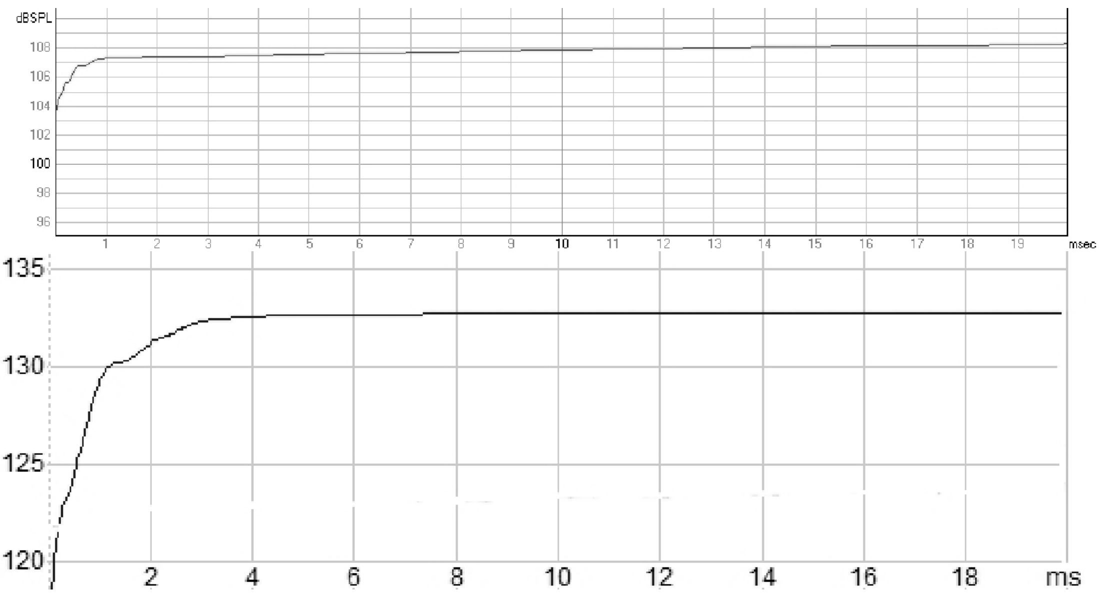


Figure 37: Cumulative energy curve [dB] for loudspeaker position A2 in surround studio. Top graph presents the measured CEC, the lower graph the calculated CEC.

The measured and calculated CEC of monitor A2 are very similar to monitor A1. The sound build-up by measurement is not as steep in the first ms for this monitor.

The total sound level in the room after 20 ms reaches 108 dB for measurement and 132 dB for calculation.

The following figures show the cumulative energy curve for monitor A3 for the first 20 ms.

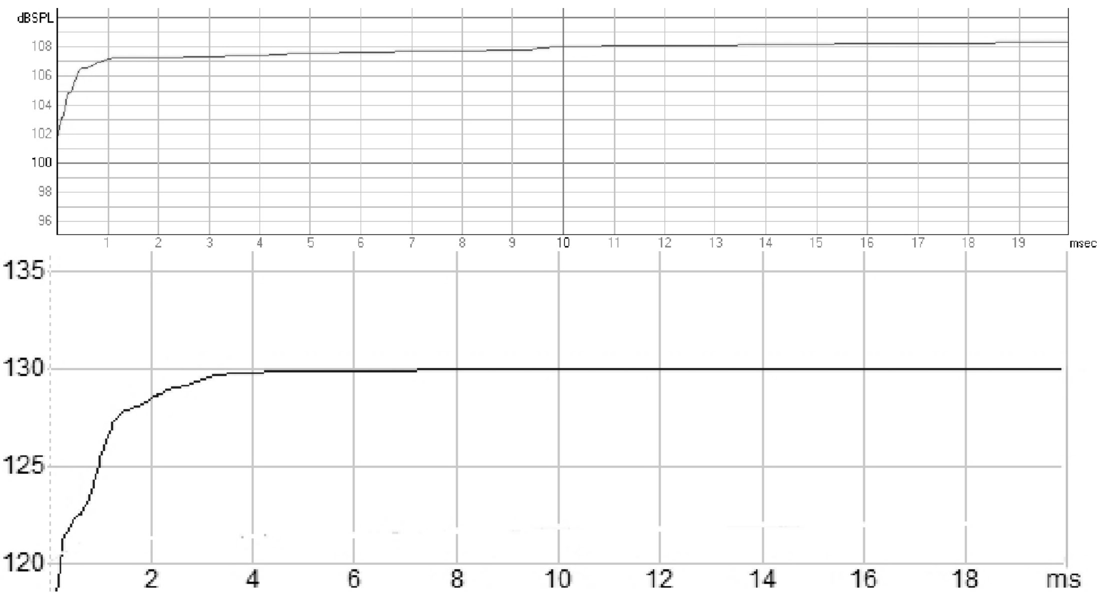


Figure 38: Cumulative energy curve [dB] for loudspeaker position A3 in surround studio. Top graph presents the measured CEC, the lower graph the calculated CEC.

The measured CEC shows that the first reflections up to 1 ms contribute mostly to the total sound level in the room. The curve is slightly increasing and reaches 108 dB at 20 ms. There is a reflection at 9.5 ms that causes a steeper increase but it is not very distinct.

The calculated CEC increases up to 4 ms and reaches a level of 130 dB, so 2 dB less than the other monitors.

4.2.5 Frequency response

The following figure shows the measured and calculated frequency response for loudspeaker position A1.

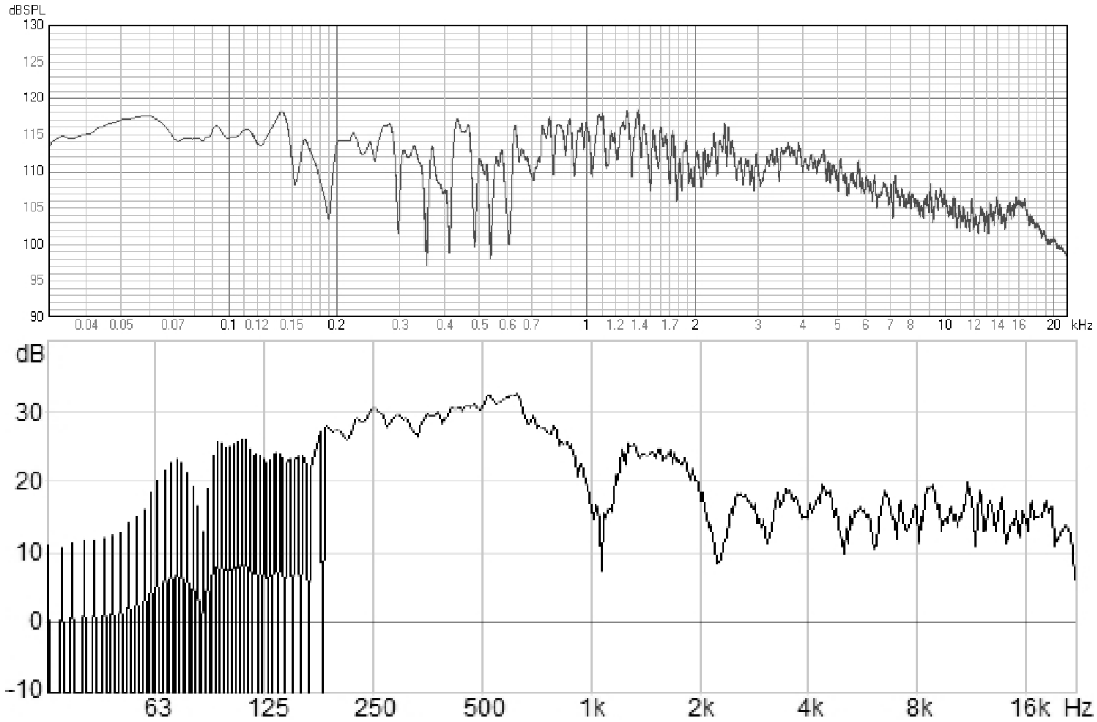


Figure 39: Frequency response [dB] for loudspeaker position A1 in surround studio. Top graph presents the measured FR, the lower graph the calculated FR.

The frequency responses do not show much correspondence.

The measured FR has a strong dip at 190 Hz. The FR is decreasing after 2 kHz. Before it is quite flat.

The calculated FR shows no results up to 200 Hz. There is a strong dip at 1.1 kHz. For higher frequencies the FR is flat and decreases rapidly after 18 kHz.

The following figure shows the measured and calculated frequency response for loudspeaker position A2.

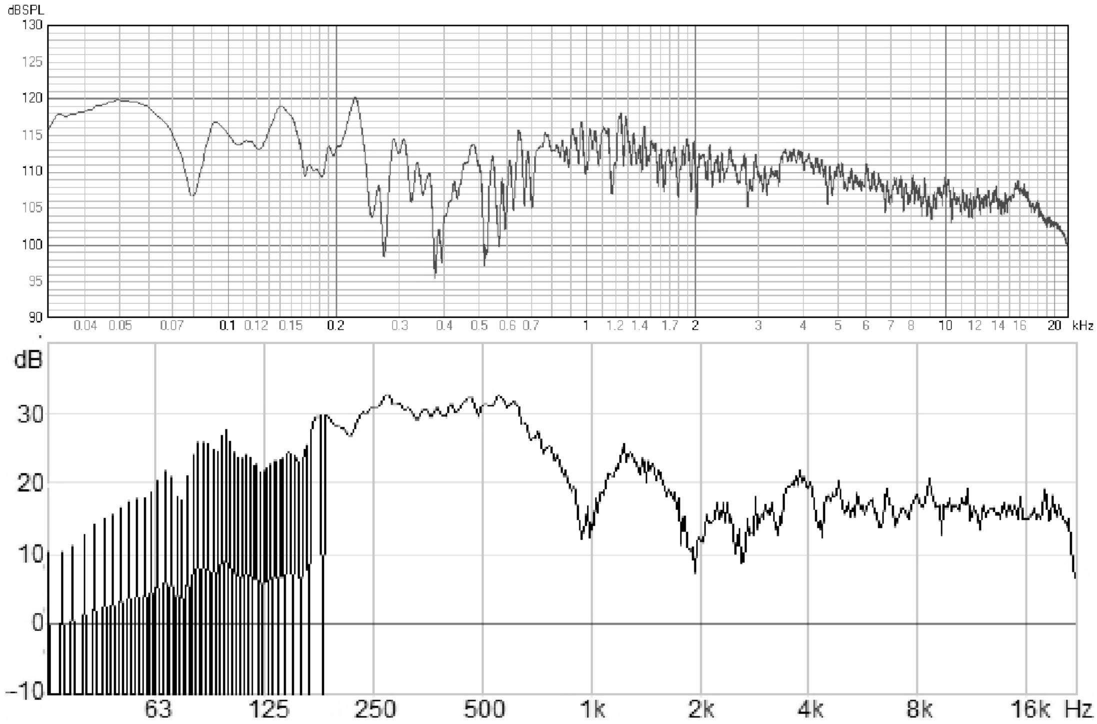


Figure 40: Frequency response [dB] for loudspeaker position A2 in surround studio. Top graph presents the measured FR, the lower graph the calculated FR.

The FR for monitor A2 by measurement shows a dip at 80 Hz and a strong dip at 270 Hz. The curve is more or less flat up to 2 kHz and decreases for higher frequencies.

The FR by calculation shows no reliable results up to 200 Hz. There is a strong dip at 900 Hz. After 2 kHz the FR is flat and decreases rapidly after 18 kHz.

The following figure shows the measured and calculated frequency response for loudspeaker position A3.

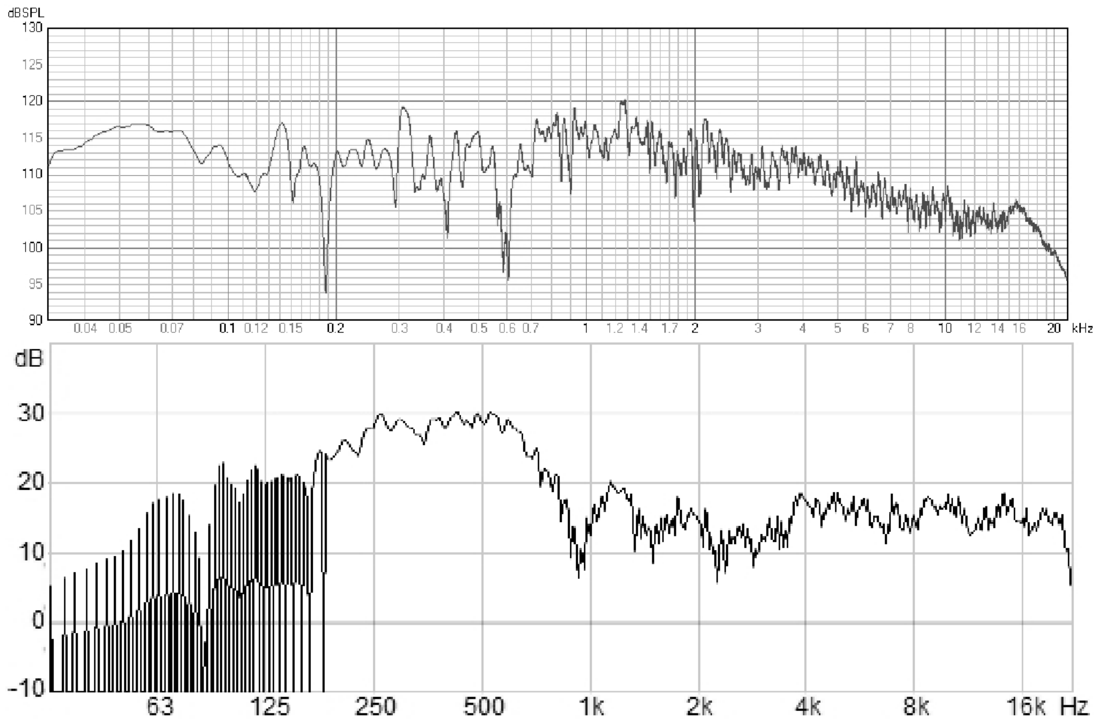


Figure 41: Frequency response [dB] for loudspeaker position A3 in surround studio. Top graph presents the measured FR, the lower graph the calculated FR.

The measured frequency response with monitor A3 contains a strong dip at 190 Hz. The FR is flat up to 2 kHz and decreases for higher frequencies.

The FR by calculation behaves similar for monitor A3 than for A2. The FR by calculation is only reliable after 200 Hz. There is a strong dip at 900 Hz. After 2 kHz the FR is flat and decreases rapidly after 18 kHz.

4.3 Studio 42

The measurements and calculations in Studio 42 were performed with two loudspeaker positions (see section 3). The results are presented as a comparison between measurement and calculation.

4.3.1 EDT, T20 and T30

The following figure shows the EDT, T20 and T30 for loudspeaker positions A0 and A1.

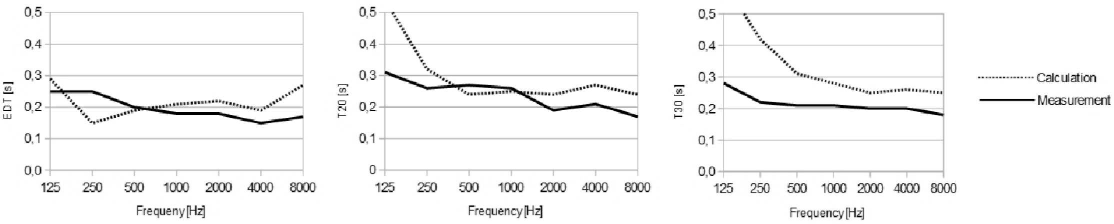


Figure 42: EDT, T20 and T30 [s] loudspeaker position A0 in studio 42.

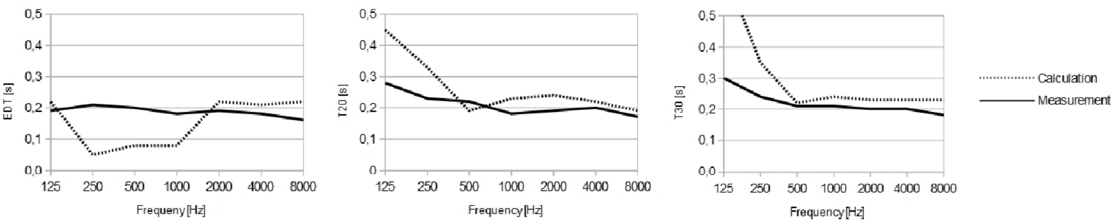


Figure 43: EDT, T20 and T30 [s] loudspeaker position A1 in studio 42.

Starting with the early decay time , it can be seen that the overall shape corresponds quite well from the 1 kHz octave band . Lower frequencies below 1 kHz are underestimated. For loudspeaker position A0, the calculated EDT is following the shape of the measured EDT but exaggerates for 8 kHz.
EDT for loudspeaker position A1 is flatter than for A0.
Looking at T20, the measured and calculated results agree well from 500 Hz on. The octave band 125 Hz takes very high values for the calculated T20. The measurement tends to do so as well but not as much.
T30 for loudspeaker position A0 differs more between measurement and calculation than for loudspeaker position A1.

4.3.2 Impulse response

The following figure shows the impulse response in mPa (measured) and relative 1 m on axis (calculated) for the first 20 ms after the direct sound.

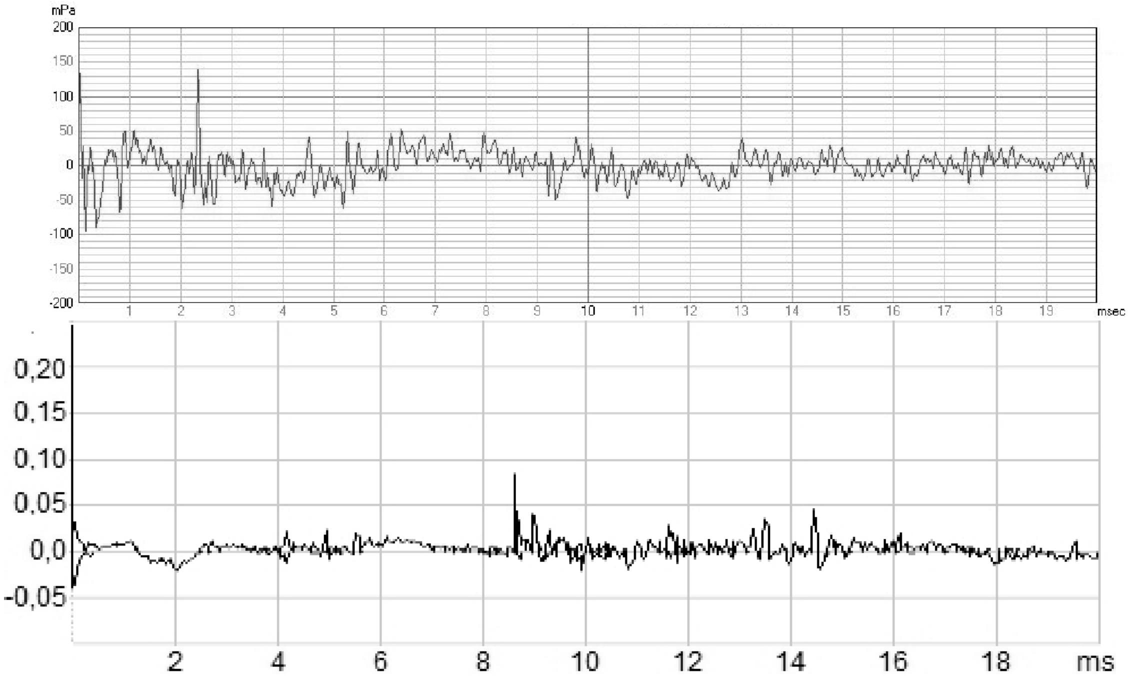


Figure 44: Impulse response for loudspeaker position A0 in studio 42. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

Compared to the calculated one, the measured IR has a weak direct sound. The first reflection occurs after around 2 ms. No other reflections seem to be dominant.
The most distinct reflections in the calculated IR appear at around 9 followed by some minor reflections around 14 ms.

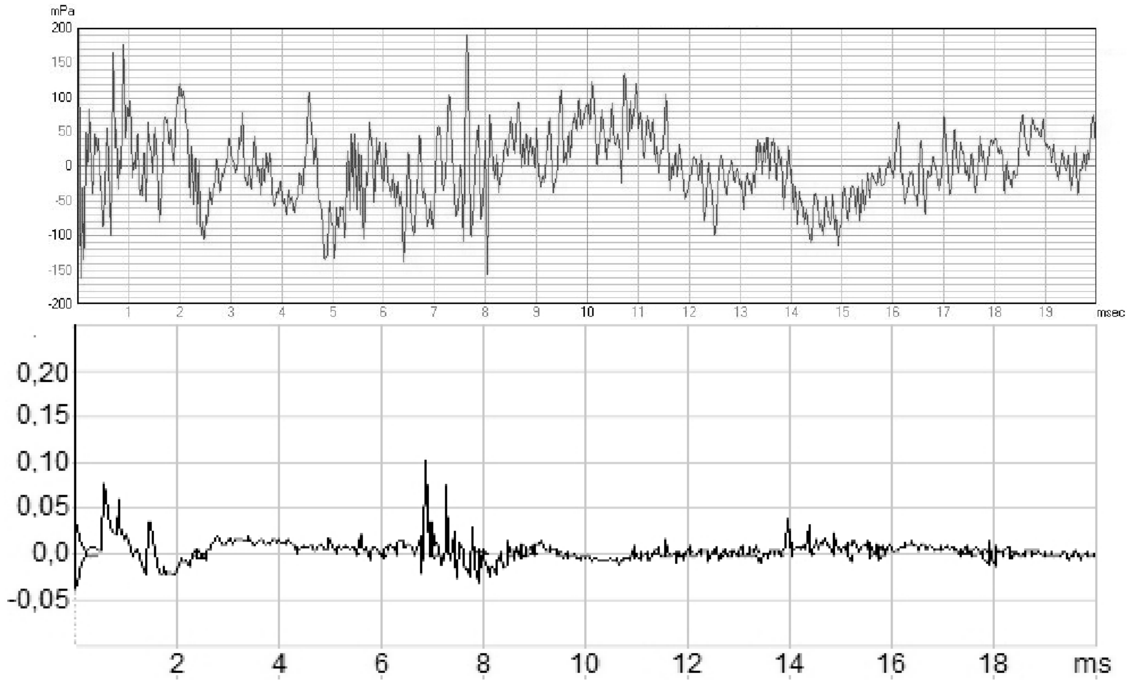


Figure 45: Impulse response for loudspeaker position A1 in studio 42. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

The direct sound from the measurement is stronger than for loudspeaker position A0. There are a lot of distinct reflections in the measured IR.
The first three reflections up to 2 ms correspond quite well in time between measurement and calculation. The group of reflections between 7 ms and 8 ms have also a good correspondence.
Later reflections correspond less in time.

4.3.3 Energy time curve

The figure below shows the energy time curve for the loudspeaker position A0 for the first 20 ms.

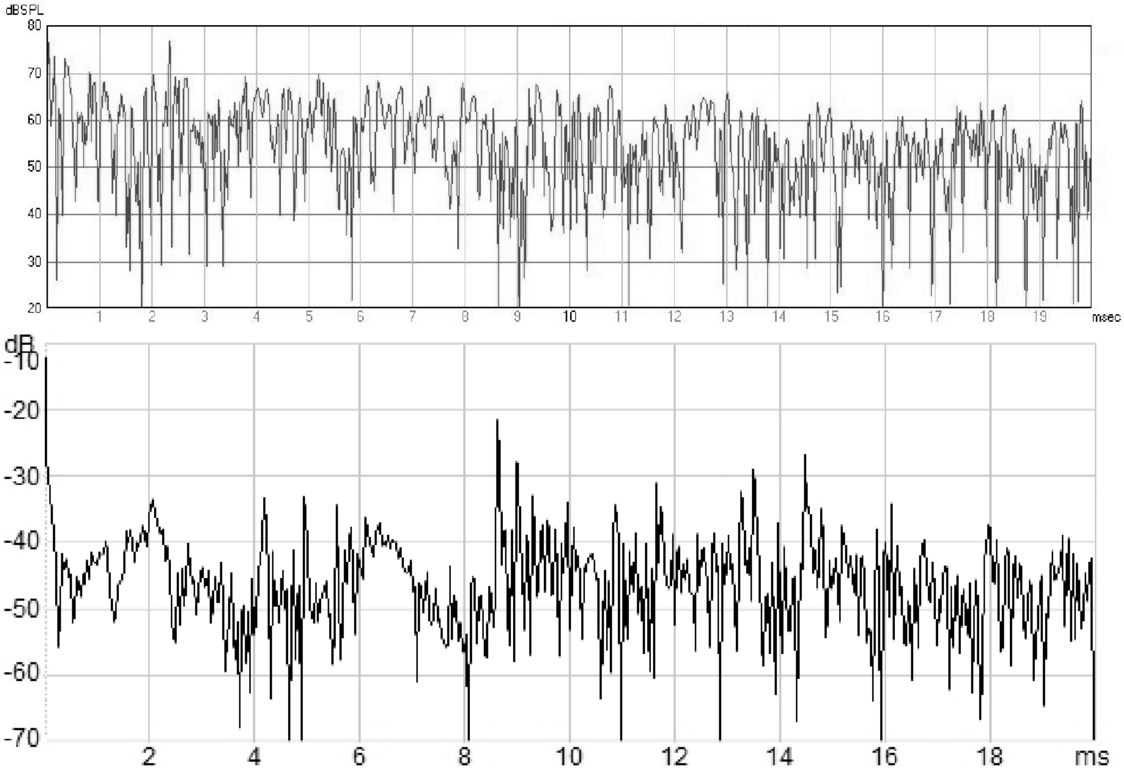


Figure 46: Energy time curve [dB] for loudspeaker position A0 in Studio 42. Top graph presents the measured ETC, the lower graph the calculated ETC.

The energy time curve from the measurement shows that the direct sound is very weak. One reflection just after 2 ms is equally strong than the direct sound. All other reflections up to 6 ms are 5 dB lower than the direct sound, later reflections at least 10 dB.

The calculated ETC is normalized to the SPL re 1 m on axis which is actually higher than the direct sound. The most dominant reflection occurs at 9 ms.

There is not much correspondence between the two graphs.

The following figure shows the energy time curve for the loudspeaker position A1 for the first 20 ms.

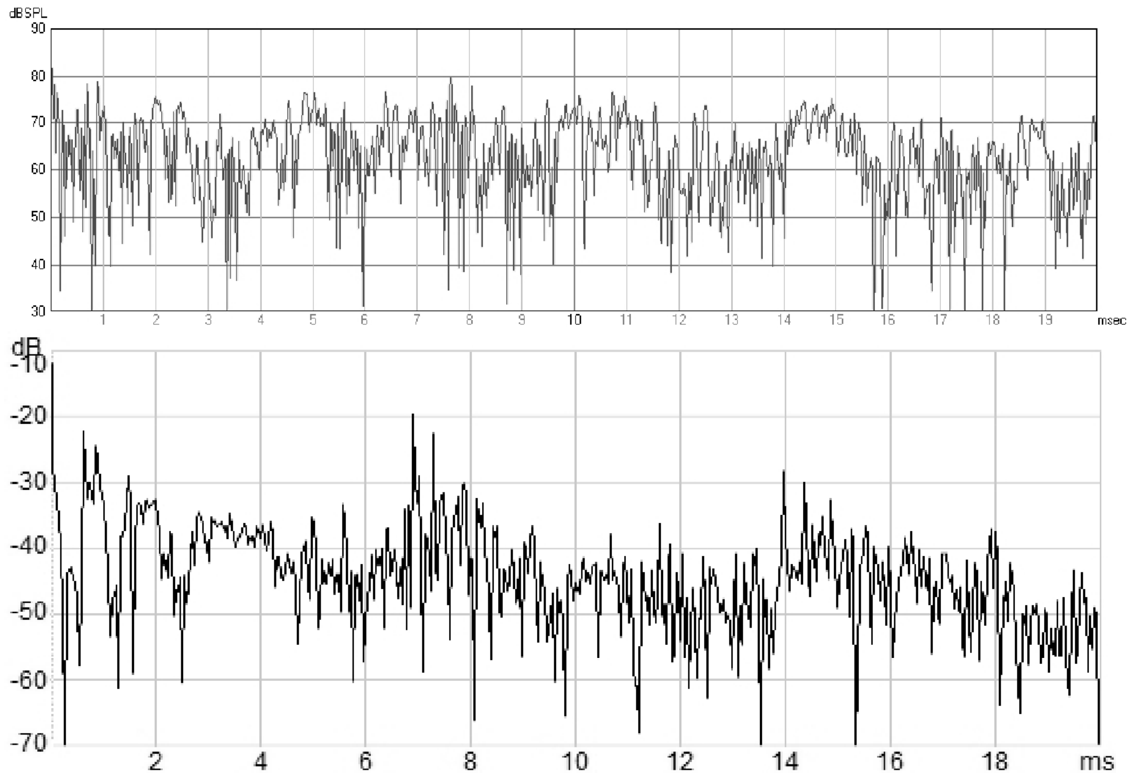


Figure 47: Energy time curve [dB] for loudspeaker position A1 in Studio 42. Top graph presents the measured ETC, the lower graph the calculated ETC.

The direct sound is 6 dB stronger than for the previous loudspeaker position. There are several reflections that are less than 5 dB weaker than the direct sound: three reflections up to 1 ms, 7.5 ms and 8 ms. A series of other reflections are 5 dB lower than the direct sound and most reflections are 10 dB lower or more.
The strongest reflections from calculation occur at 1 ms and around 7 to 8 ms. These are ca 10 dB lower than the direct sound. All other reflections are at least 20 dB lower.

The ETC curves from measurement and calculation correspond quite well and follow a similar pattern.

4.3.4 Cumulative energy curve

The cumulative energy curve allows to judge the importance of the reflection to the overall energy (see section 3.4).

The following figures show the cumulative energy curve for loudspeaker position A0 for the first 20 ms.

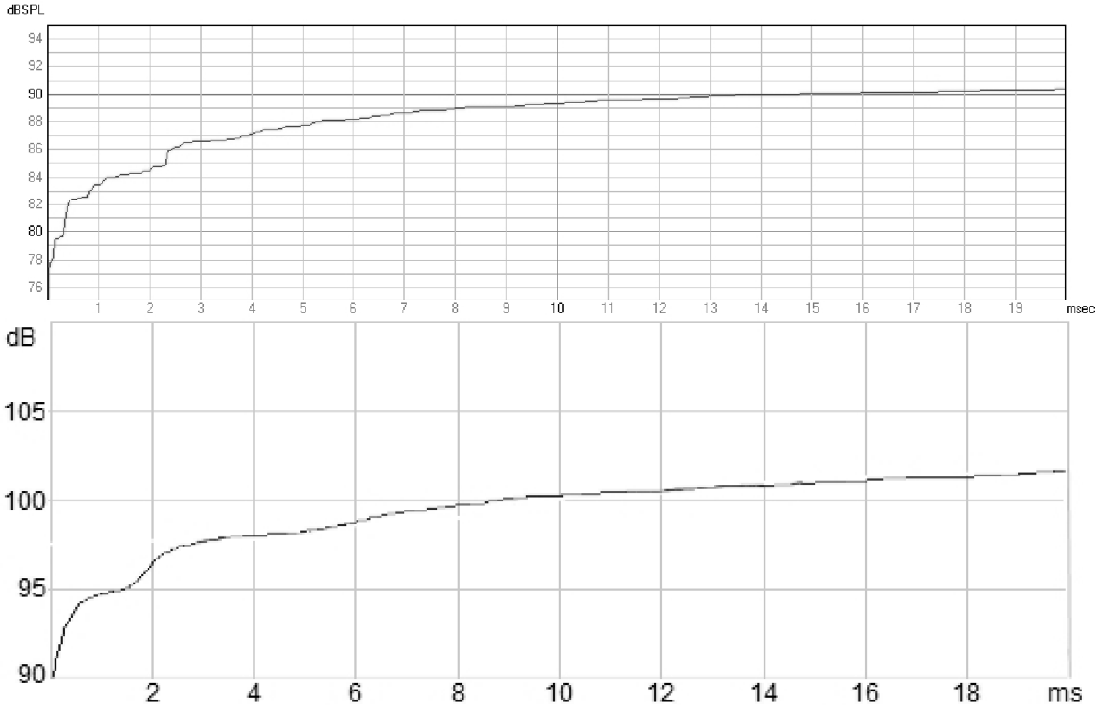


Figure 48: Cumulative energy curve [dB] for loudspeaker position A0 in Studio 42. Top graph presents the measured CEC, the lower graph the calculated CEC.

The cumulative energy curves correspond quite well in slope from 6 ms on.
The measured slope is increasing in the first 20 ms which means that they are a lot of reflections that contribute to the sound build-up in studio 42. Most contributing are the first reflections up to 4 ms. In the measured CEC the reflections are easier to distinguish than in the smoother calculated one.

The calculated CEC shows stronger reflections up to 6 ms. Thereafter the slope increases similarly to the measured one.

The following figures show the cumulative energy curve for loudspeaker position A1 for the first 20 ms.

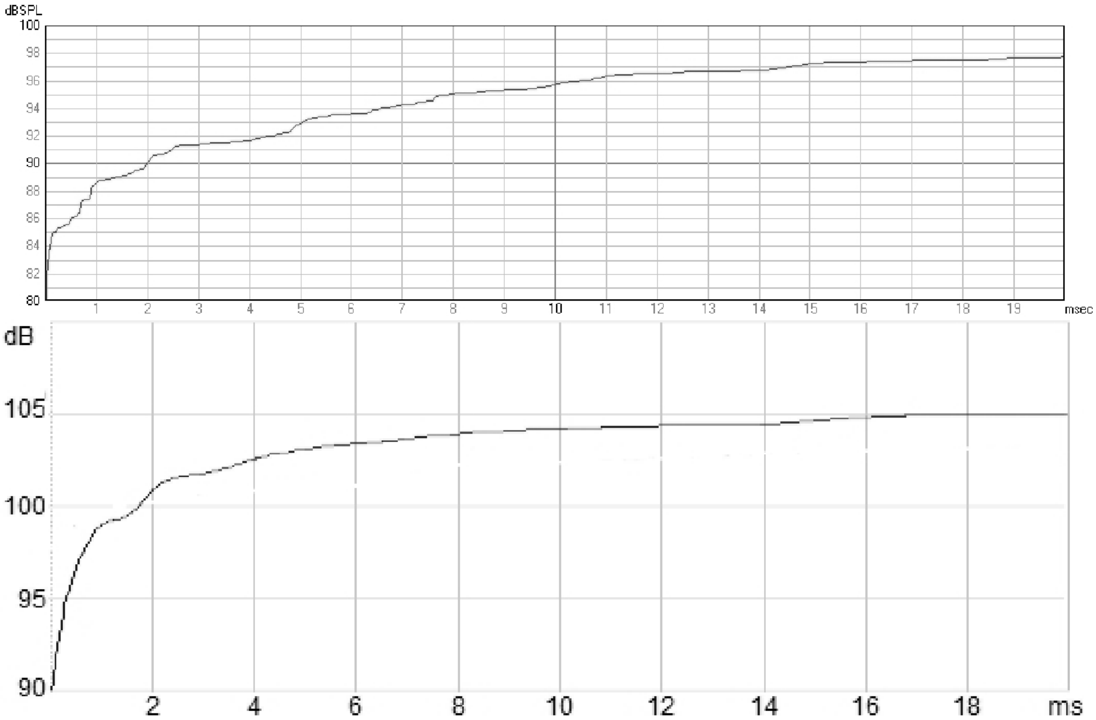


Figure 49: Cumulative energy curve [dB] for loudspeaker position A1 in Studio 42. Top graph presents the measured CEC, the lower graph the calculated CEC.

Even though the IR and ETC agreed quite well for loudspeaker position A1, the cumulative energy curve is not corresponding so well at the first glimpse.

The slope by measurement is steeper than by calculation. The room needs more time to build up the sound. Reflections up to 15 ms are involved.

The calculated CEC does not shows as many distinct reflections. The most distinguishable reflections occur at 1 ms and 3 ms. Later reflections do contribute less as the slope flattens out.

4.3.5 Frequency response

The following figure shows the measured and calculated frequency response for loudspeaker position A0.

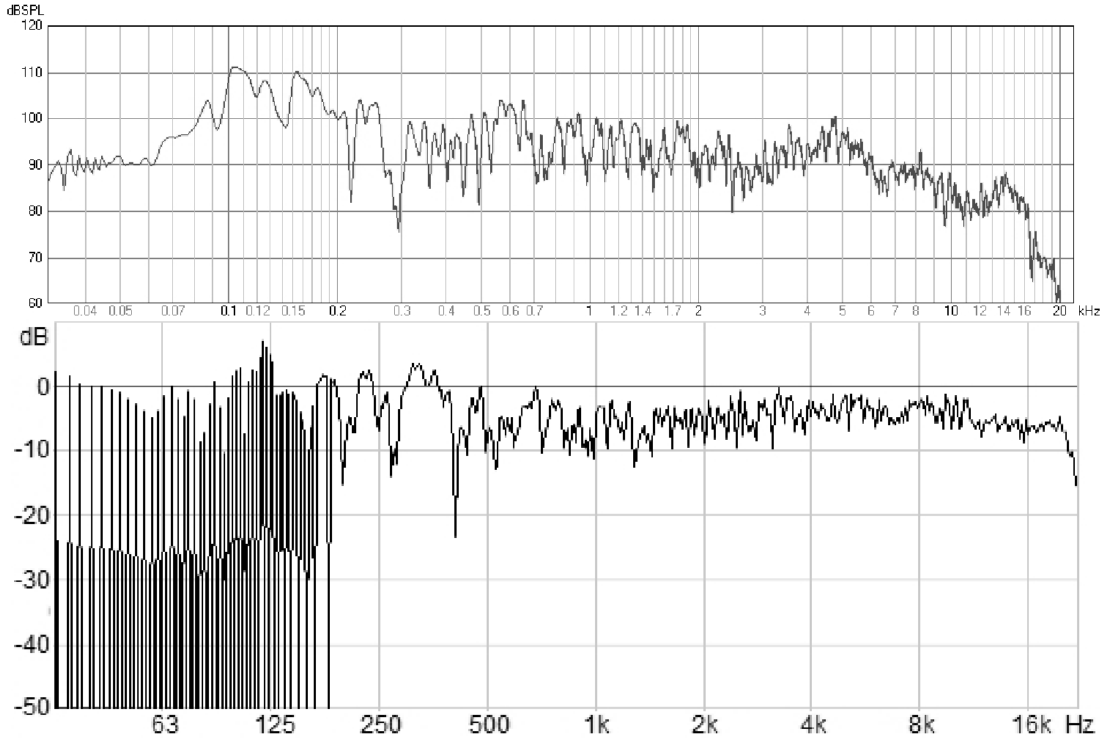


Figure 50: Frequency response [dB] for loudspeaker position A0 in studio 42. Top graph presents the measured FR, the lower graph the calculated FR.

The frequency response for both the calculated and the measured result shows interference pattern. The interferences will be studied more in detail in the discussion in section 5.

The measured FR for loudspeaker A0 shows low levels up to around 63 Hz. The response is flat betweee 200 and 5 kHz and decreases for higher frequencies. At 18 kHz there is a strong dip

The calculated FR shows weird levels up to 160 Hz. The interference pattern with peaks and dips after 200 Hz correspond well between measurement and calculation. Most peaks and dips correspond in frequency.

The calculated FR is flat up to 12 kHz and decreases slightly for higher frequencies.

The following figure shows the measured and calculated frequency response for loudspeaker position A1.

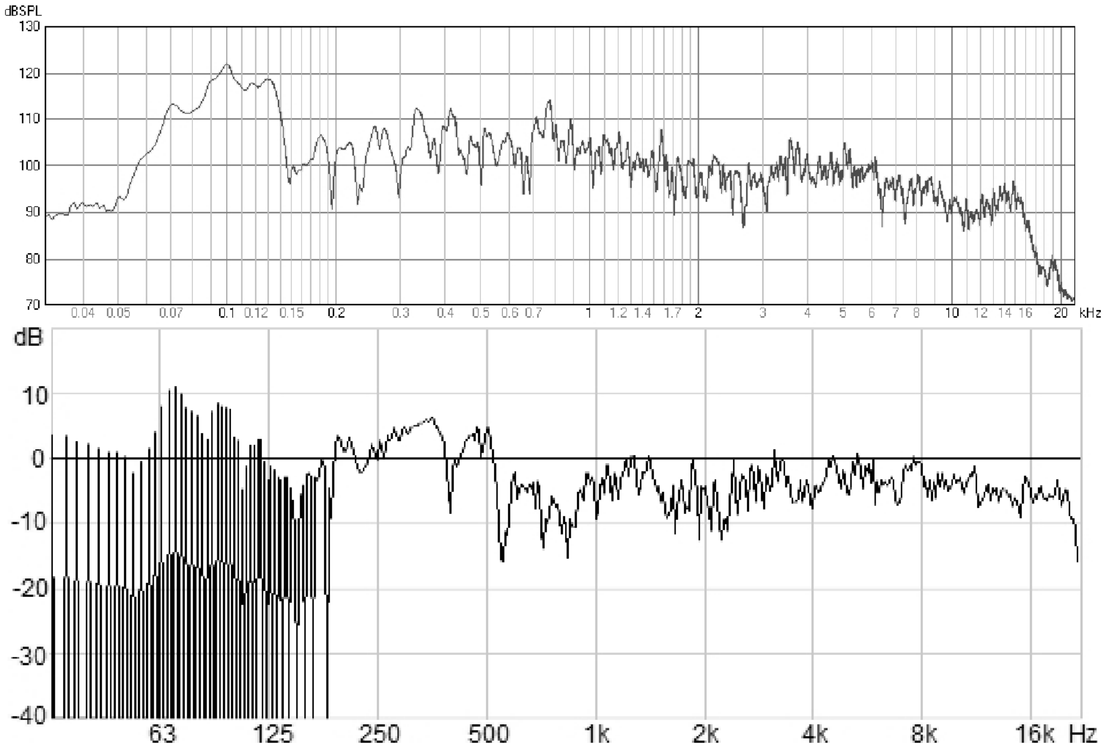


Figure 51: Frequency response [dB] for loudspeaker position A1 in studio 42. Top graph presents the measured FR, the lower graph the calculated FR.

Again, the measured FR shows low levels up to 63 Hz. The curve is flat between 200 Hz and 5 kHz and decreases thereafter.

The interference patterns of peaks and dips do not correspond well. Only the dip at 190 Hz corresponds.

The calculated FR contains weird levels up to 160 Hz. The frequency response is quite flat up to 18 kHz.

4.4 Studio 32

4.4.1 EDT, T20 and T30

The following figure shows the EDT, T20 and T30 for the used loudspeaker position.

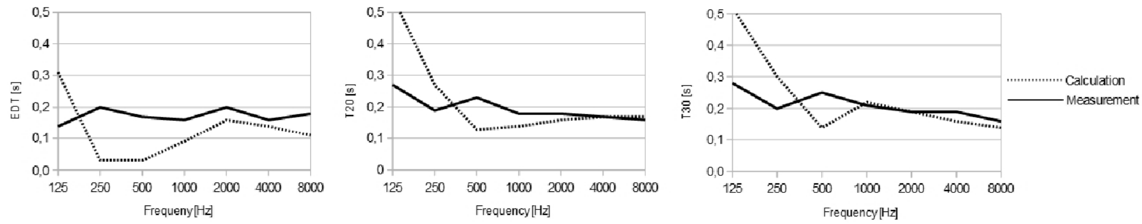


Figure 52: EDT, T20 and T30 [s] loudspeaker position A0 in studio 32.

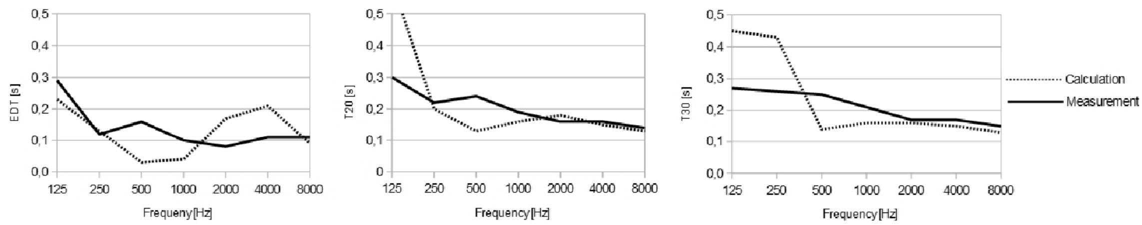


Figure 53: EDT, T20 and T30 [s] loudspeaker position A1 in studio 32.

The above figures show the same characteristics as the previous rooms: the EDT deviates much between measurement and calculation whereas T20 and T30 shows better correspondence.

Loudspeaker position A0 gives a flat measured EDT. The calculated EDT is underestimated for all frequencies apart from octave band 125 Hz. The general pattern agrees from octave band 1 kHz.
Loudspeaker position A1 gives a decreasing measured EDT. The values by calculation are underestimated to 1 kHz and too high for higher frequencies.

The reverberation times T20 and T30 are decreasing from low to high frequencies in studio 32. The calculation results in very long reverberation times for octave band 125 Hz and slightly longer for octave band 250 Hz. Octave band 500 Hz is underestimated in T20 and T30 for both loudspeaker positions.
Otherwise, the results show good agreement from octave band 1 kHz.

4.4.2 Impulse response

The following figure shows the impulse response in mPa (measured) and relative 1 m on axis (calculated) for the first 20 ms after the direct sound. The graphs are grouped as a comparison of measurement and calculation for the used loudspeaker positions.

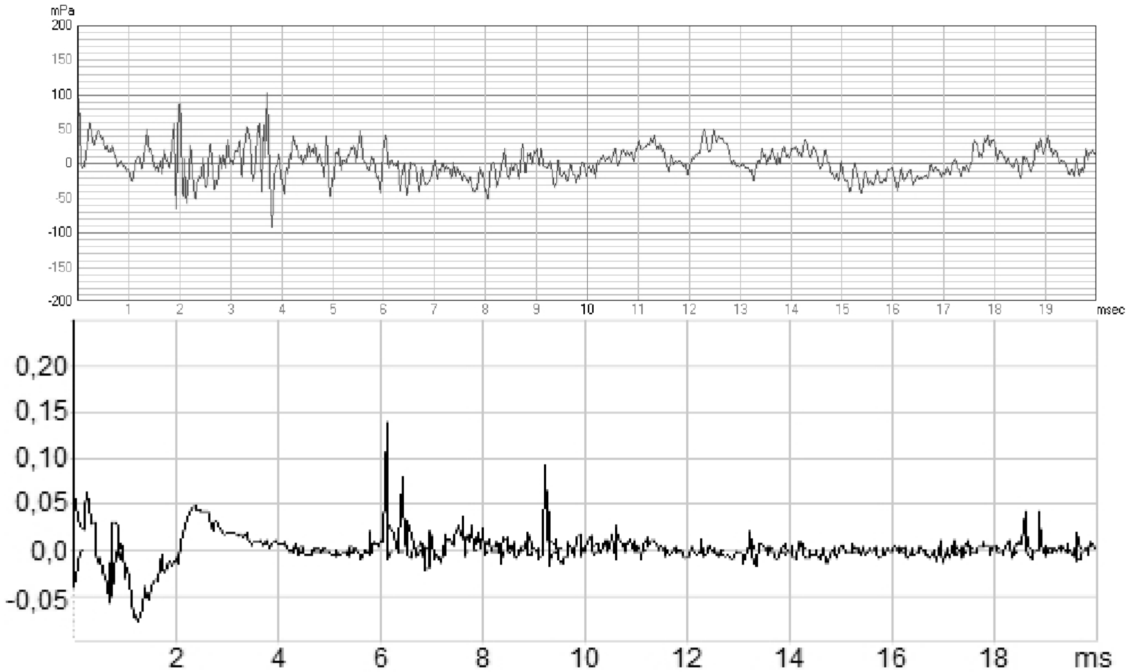


Figure 54: Impulse response for loudspeaker position A0 in studio 32. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

The impulse response for loudspeaker position A0 contains a weak direct sound for the measurement.

The most dominant reflections in the measured IR occur in the first 4 ms. The calculated IR shows a similar pattern up to 2.5 ms but slightly shifted in time. The reflections are less distinct than by measurement.
The calculated IR shows the most dominant reflections at 6 and 9 ms.

The following figures show the impulse response for loudspeaker position A1 for the first 20 ms.

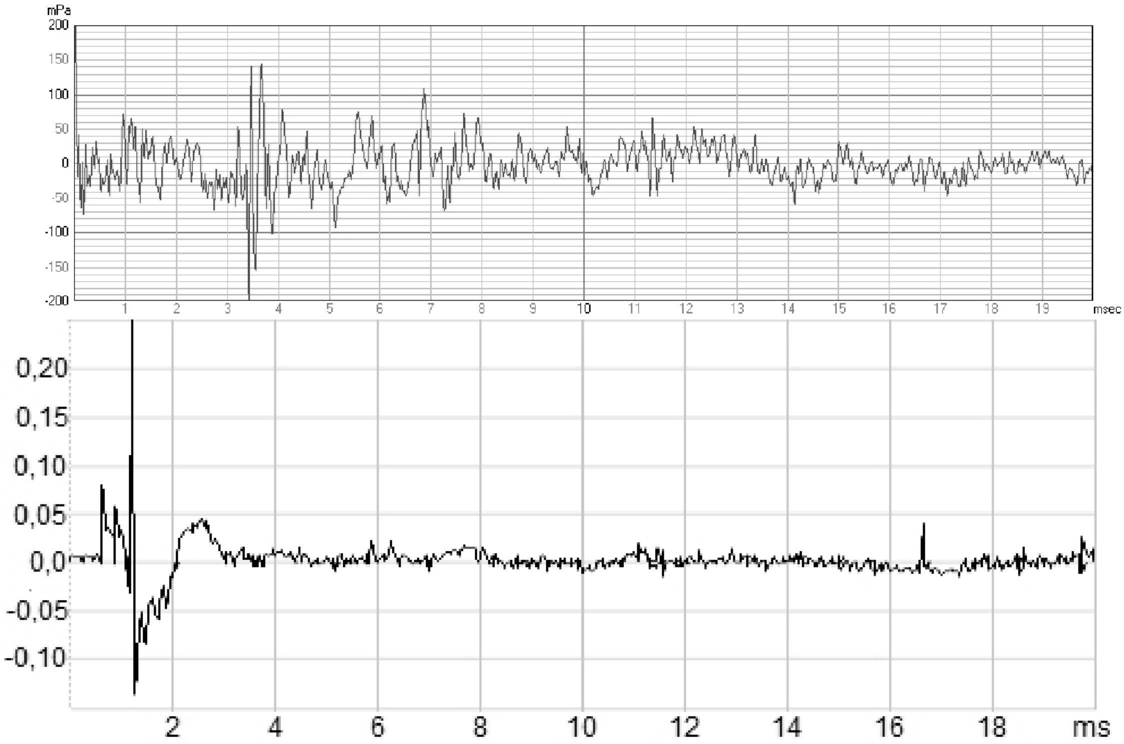


Figure 55: Impulse response for loudspeaker position A1 in studio 32. Top graph presents the measured IR [mPa], the lower graph the calculated IR [Pa].

For loudspeaker position A1, the direct sound by measurement is stronger than for the previous position. On the other hand, there is no direct sound for the calculated IR.

The results do not agree at all. The measured IR shows the strongest reflections at 3.5 ms and 7 ms; the calculated IR at 1.5 ms.

4.4.3 Energy time curve

The figure below shows the energy time curve for the loudspeaker position A0 for the first 20 ms.

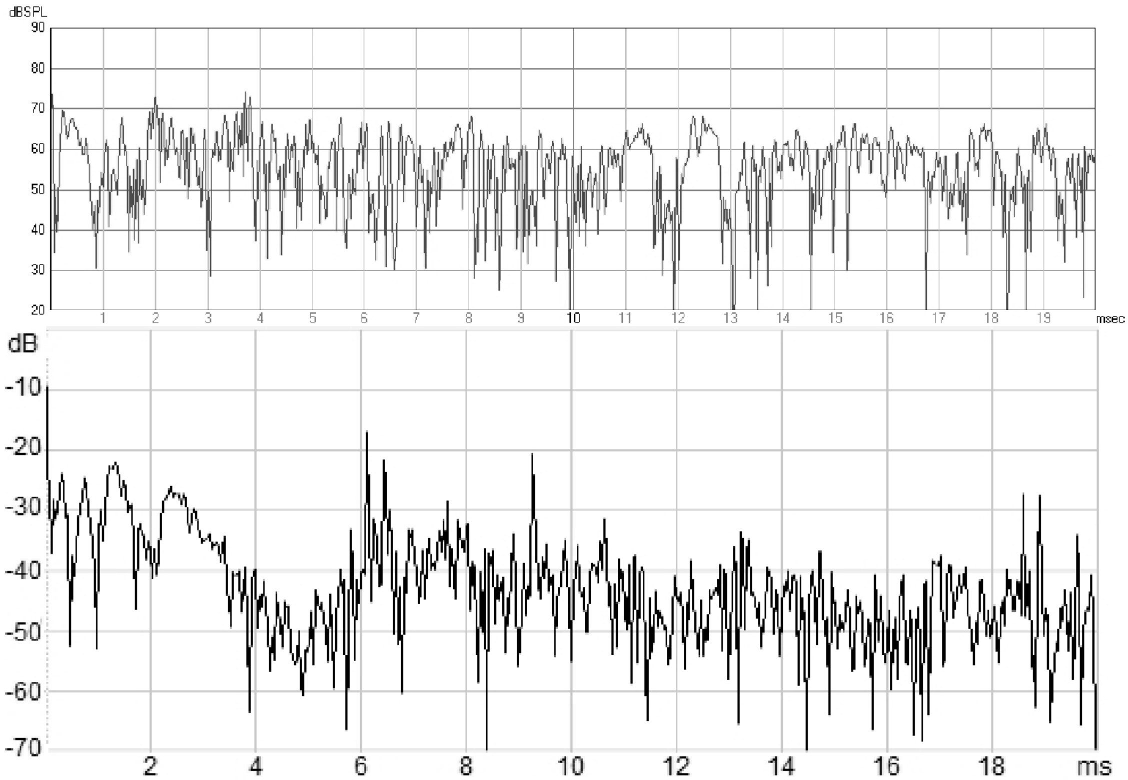


Figure 56: Energy time curve [dB] for loudspeaker position A0 in Studio 32. Top graph presents the measured ETC, the lower graph the calculated ETC.

The ETC by measurement has a low weak sound followed by two reflections at 2 and around 4 ms that are higher in level than the direct sound. Most reflections are only 5 dB lower than the direct sound.

The calculated ETC contains only few reflections that are around 10 dB lower than the direct sound. Most reflections are at least 25 dB lower.
The curves correspond well up to 2.5 ms. Later, they differ considerably.

The following figure shows the energy time curve for the loudspeaker position A1 for the first 20 ms..

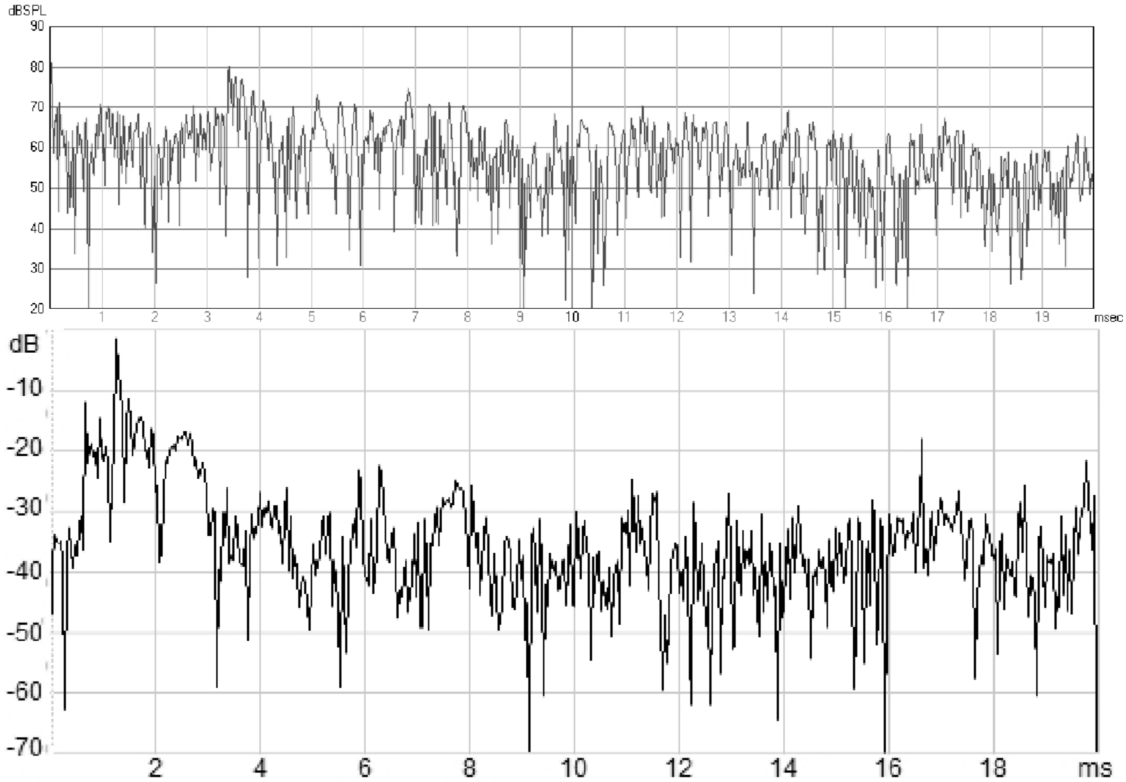


Figure 57: Energy time curve [dB] for loudspeaker position A1 in Studio 32. Top graph presents the measured ETC, the lower graph the calculated ETC.

Even though the direct sound is so weak for the calculation, the curves show good correspondence in pattern between 8 and 20 ms.

Otherwise, there is not much correspondence

4.4.4 Cumulative energy curve

The following figures show the cumulative energy curve for loudspeaker position A0 for the first 20 ms.

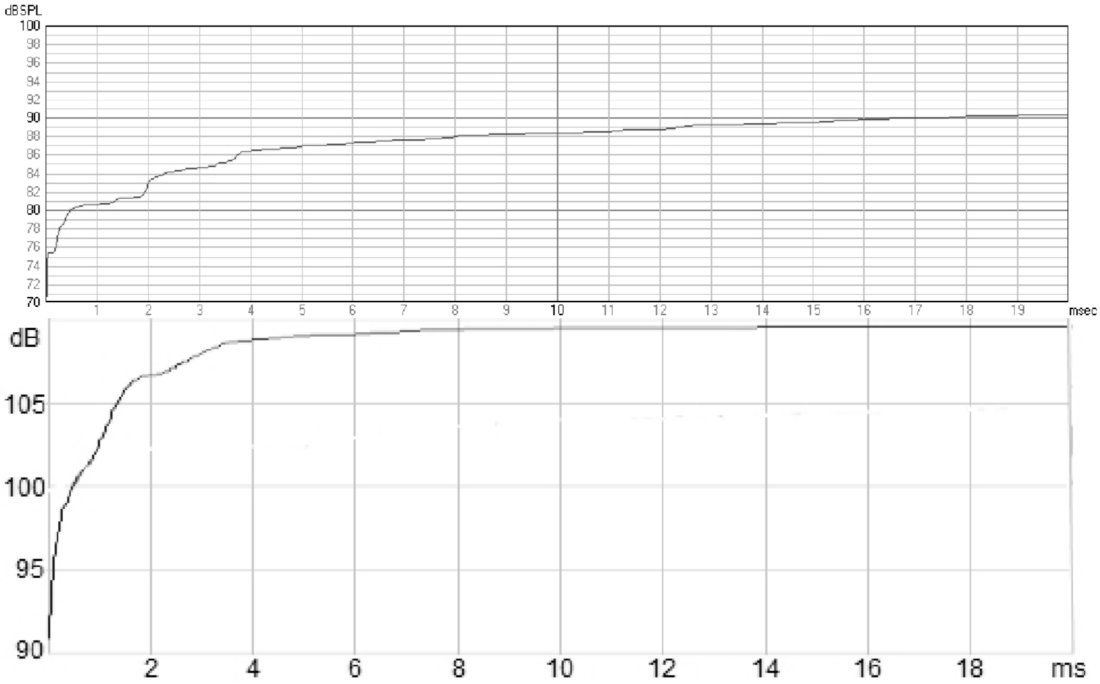


Figure 58: Cumulative energy curve [dB] for loudspeaker position A0 in Studio 32. Top graph presents the measured CEC, the lower graph the calculated CEC.

The CEC by measurement shows that several reflections in the first 4 ms are strongly involved in the sound build-up. The curve is constantly increasing and flattens out slightly at around 18 ms.

The calculated CEC builds up to 4 ms, increases slightly to 8 ms and is flat for later decay times.

The following figures show the cumulative energy curve for loudspeaker position A0 for the first 20 ms.

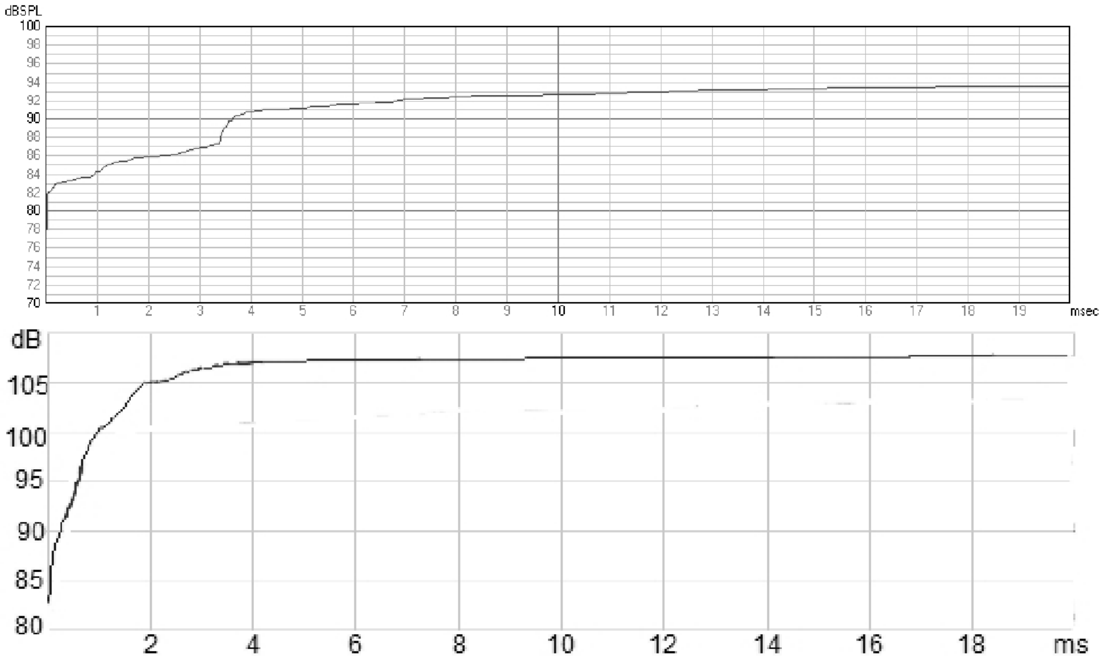


Figure 59: Cumulative energy curve [dB] for loudspeaker position A1 in Studio 32. Top graph presents the measured CEC, the lower graph the calculated CEC.

The measured CEC shows that mainly the reflection at 3.5 ms is contributing to the total sound build-up. The slope increases slightly and flattens out around 18 ms.

The calculated CEC is less steep in the first 4 ms than for loudspeaker position A0 but shows the same flatness for later decay times.

4.4.5 Frequency response

The following figure shows the measured and calculated frequency response for loudspeaker position A0.

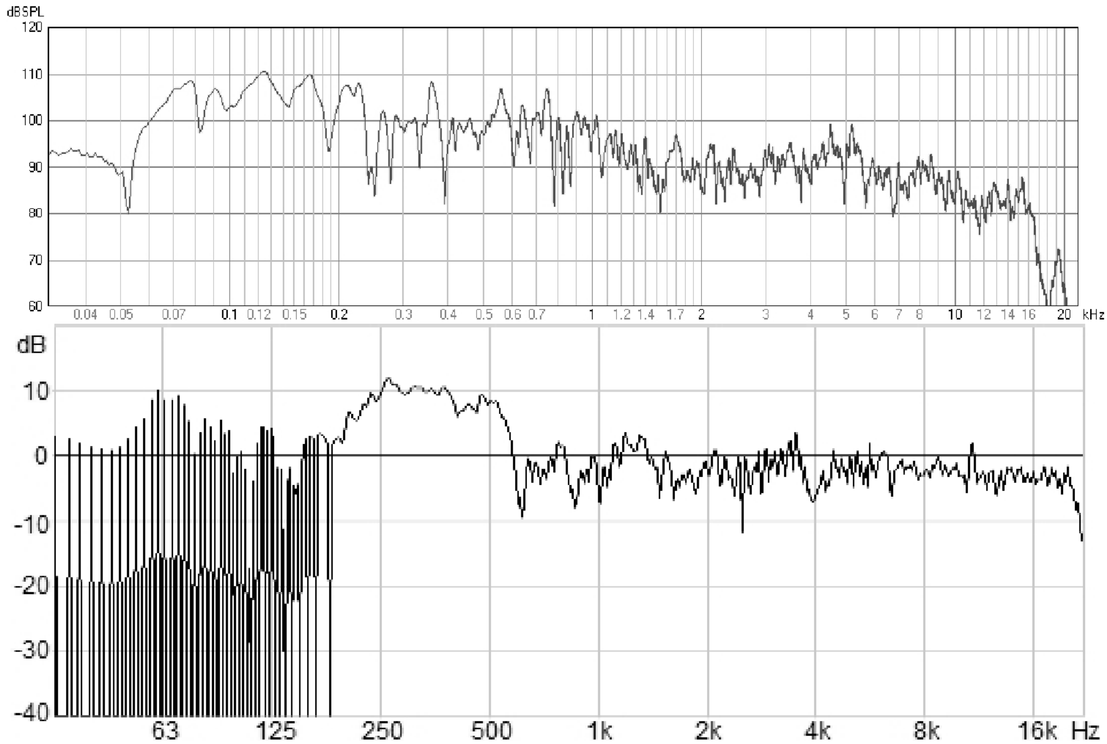


Figure 60: Frequency response [dB] for loudspeaker position A0 in studio 32. Top graph presents the measured FR, the lower graph the calculated FR.

The measured FR shows a dip at 60 Hz. The level is flat up to 1 kHz and decreases up to 1.6 kHz. Then it is flat again until 5.5 kHz and decreases slowly for higher frequencies and rapidly after 16 kHz.

The calculated FR shows no reliable results up to 200 Hz. The first dip is at 600 Hz. The curve is flat up to 18 kHz and decreases for higher frequencies.

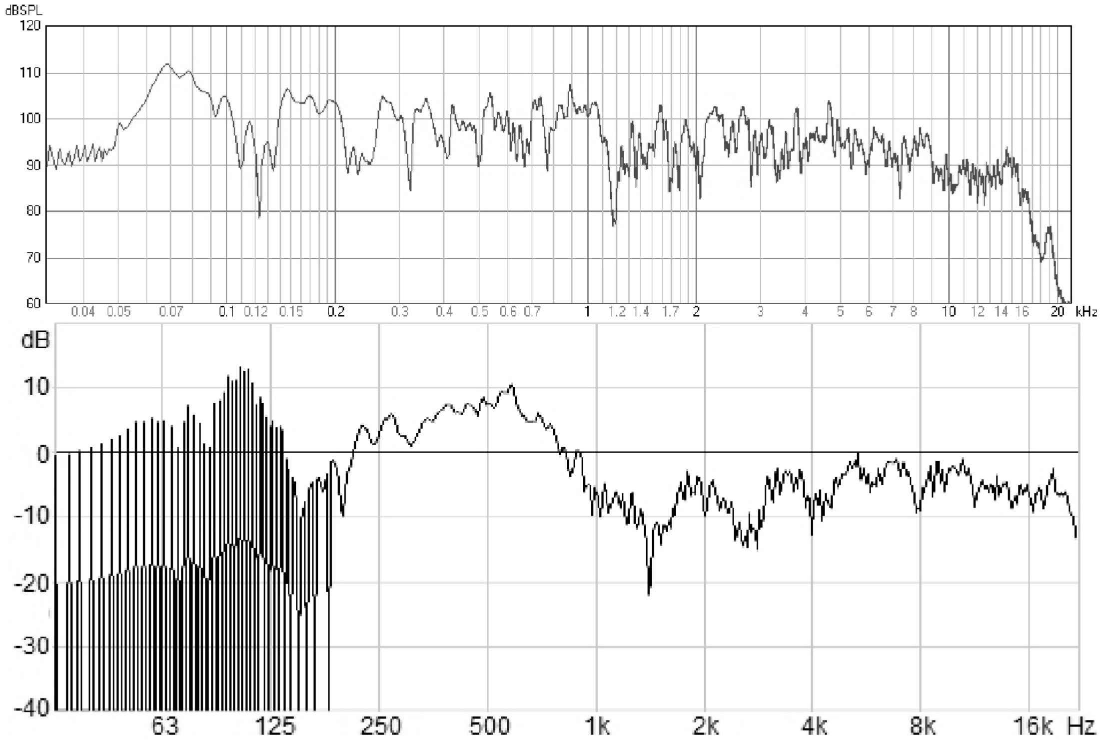


Figure 61: Frequency response [dB] for loudspeaker position A1 in studio 32. Top graph presents the measured FR, the lower graph the calculated FR.

The measured FR contains a deep dip at 125 Hz. The curve is flat up to 1 kHz and reveals a dip at 1200 Hz. Thereafter the curve stays flat and decreases steeply from 16 kHz.

The calculated FR shows unreliable values up to 200 Hz. The first dip occurs at 1.6 kHz. The curve is flat for higher frequencies and decreases after 18 kHz.

4.5 Studio 31

4.5.1 EDT, T20 and T30

The following figure shows the EDT, T20 and T30 for loudspeaker positions A0 and A1.

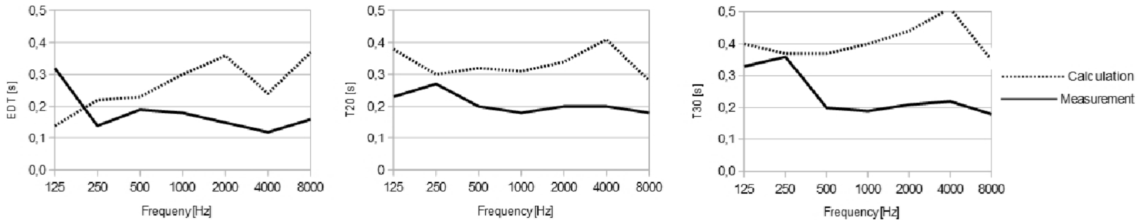


Figure 62: EDT, T20 and T30 [s] loudspeaker position A0 in studio 31.

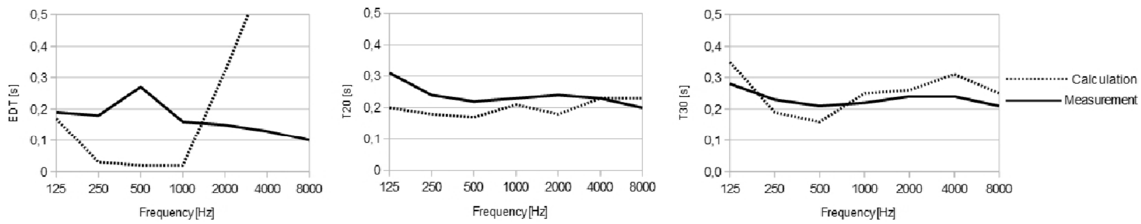


Figure 63: EDT, T20 and T30 [s] loudspeaker position A1 in studio 31.

EDT, T20 and T30 for loudspeaker position A0 do not agree well between measurement and calculation.
The calculated curve is on average 0.15 s higher than the measured curve for all three parameters.

The EDT measured and calculated with loudspeaker position A1 shows no correspondence either. The EDT by calculation is below 0.1 s up to 1 kHz and increases steeply to over 0.5 s for higher frequencies.

The calculated T20 and T30 agree better. T20 is calculated shorter than measured for all frequencies apart from 8 kHz. For the octave bands 125 Hz and 1 kHz and higher, T30 is longer than measured. The octave bands 250 Hz and 500 Hz are shorter than measured. The average difference between measurement and calculation is 0.05 s for both T20 and T30.

4.5.2 Impulse response

The following figure shows the impulse response in mPa (measured) and relative 1 m on axis (calculated) for the first 20 ms after the direct sound. The graphs are grouped as a comparison of measurement and calculation for the used loudspeaker positions.

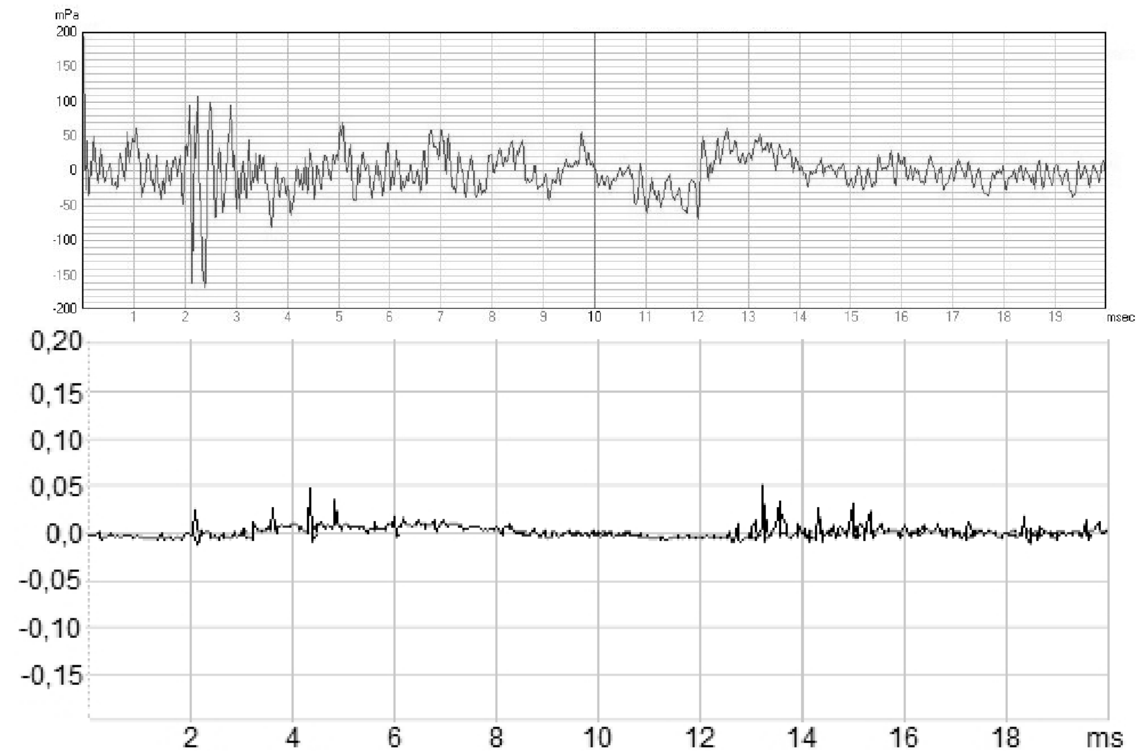


Figure 64: Impulse response for loudspeaker position A0 in studio 31. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

The impulse response that has been measured with loudspeaker position A0 shows a group of reflections around 2 ms. In general, the pressure fluctuations are around 1/4 of the direct sound.

The calculated IR contains no direct sound at all. There are some smaller reflections at 2 ms and around 5 ms that are agreeing in time with the measurement. Furthermore, there are some reflections between 13 ms and 15 ms.

The following figures show the impulse response for loudspeaker position A1 for the first 20 ms.

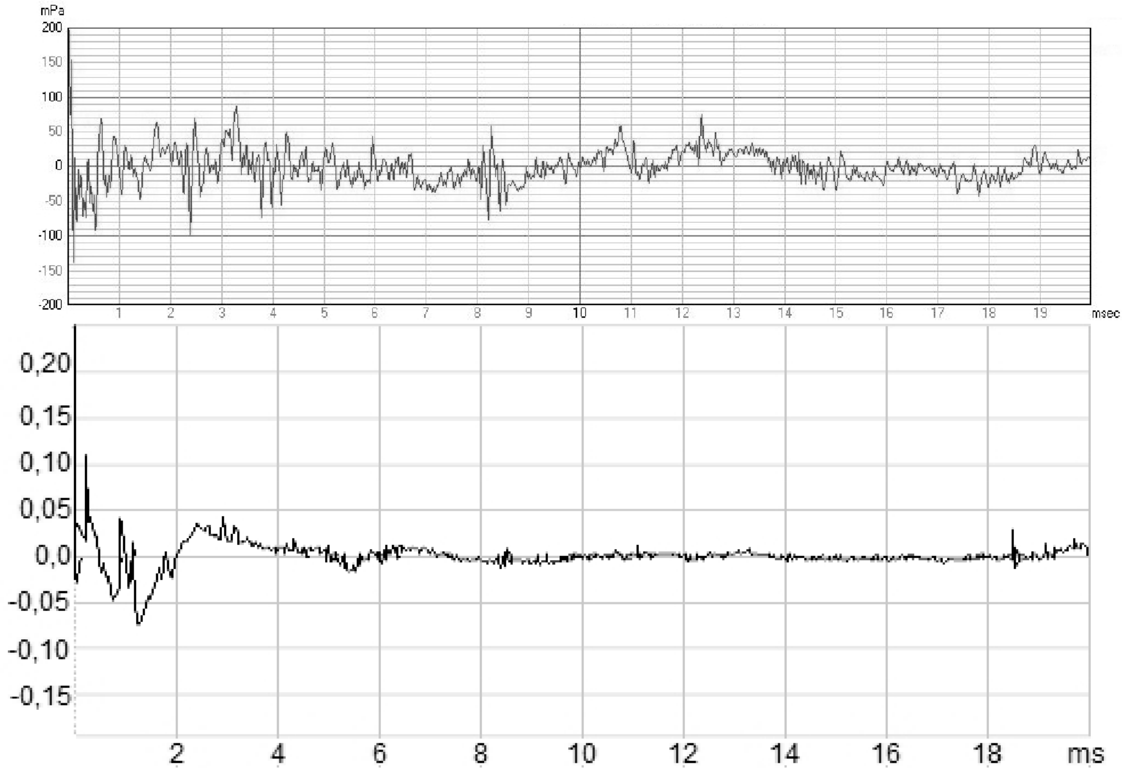


Figure 65: Impulse response for loudspeaker position A1 in studio 31. Top graph presents the measured IR [mPa], the lower graph the calculated IR.

For loudspeaker position A1, the direct sounds for both measurement and calculation are stronger than for previous loudspeaker position.

The graphs show good correspondence up to 4 ms. The calculated IR does not fluctuate that much in pressure for later decay times and is quite flat.

4.5.3 Energy time curve

The figure below shows the energy time curve for the loudspeaker position A0 for the first 20 ms.

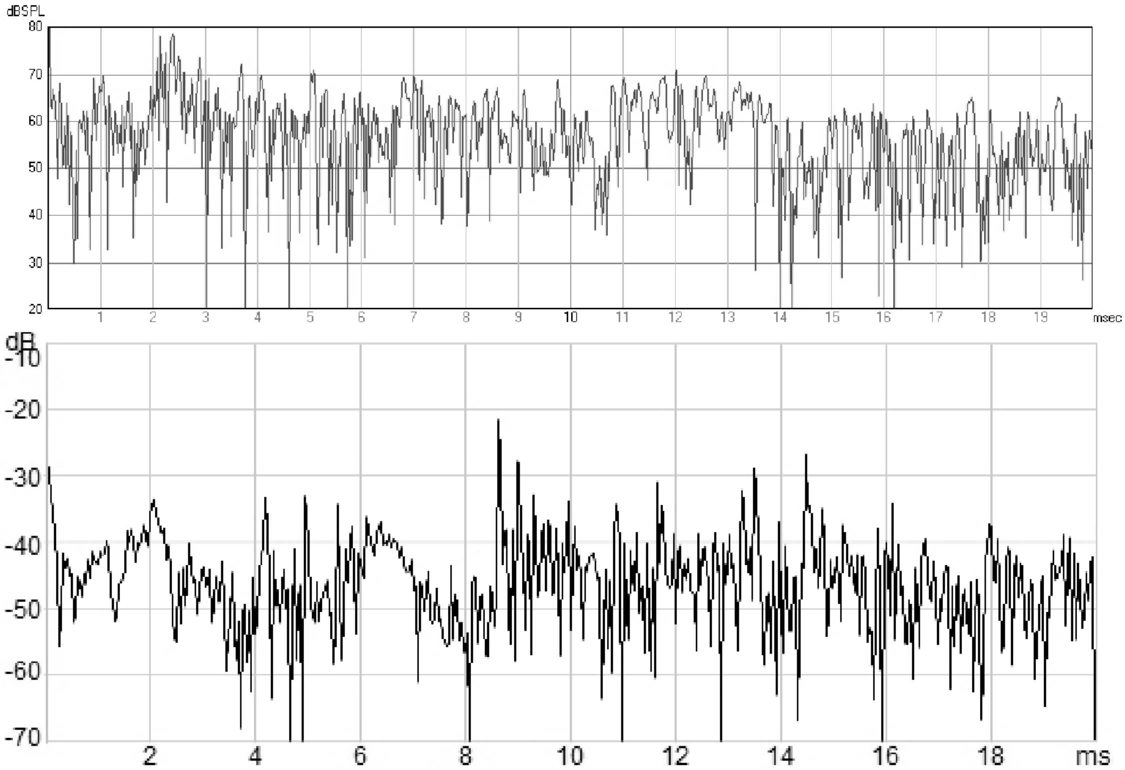


Figure 66: Energy time curve [dB] for loudspeaker position A0 in Studio 31. Top graph presents the measured ETC, the lower graph the calculated ETC.

Although the direct sound is so low by calculation, the ETCs show some correspondence up to 6 ms. The reflection peaks are slightly shifted.
For later decay times, there is not much correspondence.
The reflections up to 1 ms in the measured ETC are at least 10 dB lower than the direct sound in the measured curve. Later reflections are at least 15 dB lower.

The following figure shows the energy time curve for the loudspeaker position A1 for the first 20 ms.

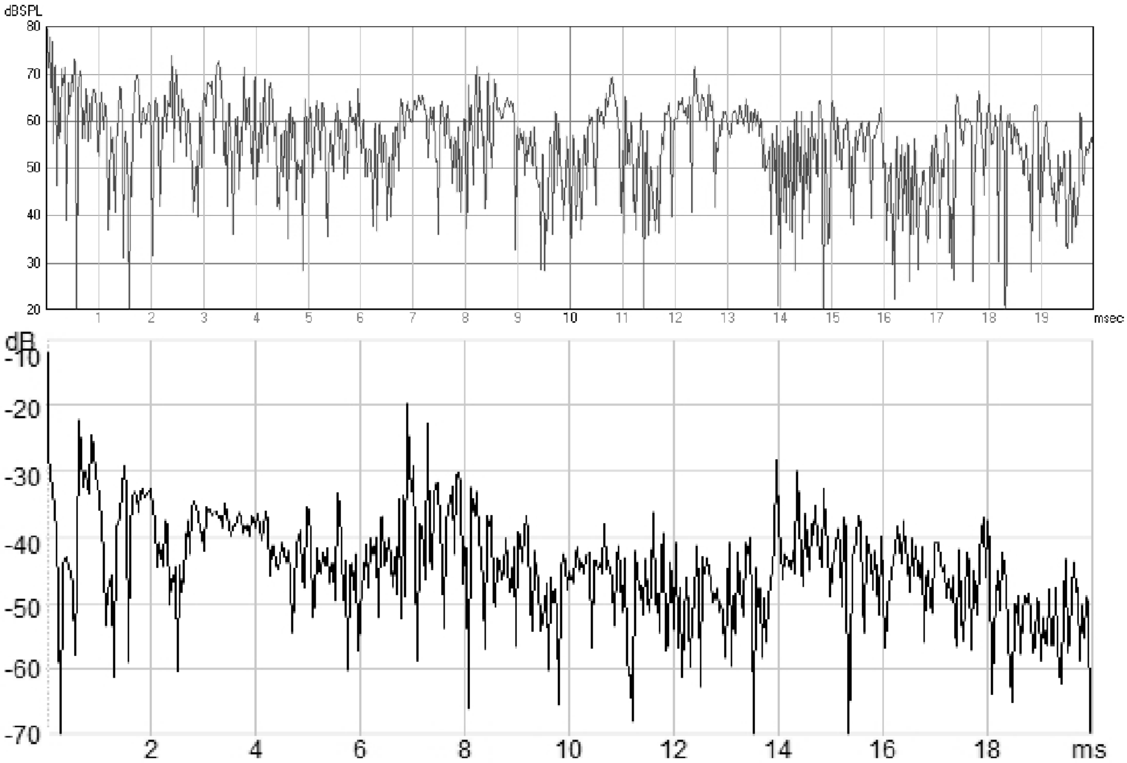


Figure 67: Energy time curve [dB] for loudspeaker position A1 in Studio 31. Top graph presents the measured ETC, the lower graph the calculated ETC.

The measured and calculated energy time curves show some agreeing dips and peaks in the first 6 ms.
Only a few reflections are around 10 dB lower than the direct sound. All other reflections are at least 15 dB lower than the direct sound.

The reflections in the calculated ETC are much lower in level than the measured ones.

4.5.4 Cumulative energy curve

The following figures show the cumulative energy curve for loudspeaker position A0 for the first 20 ms.

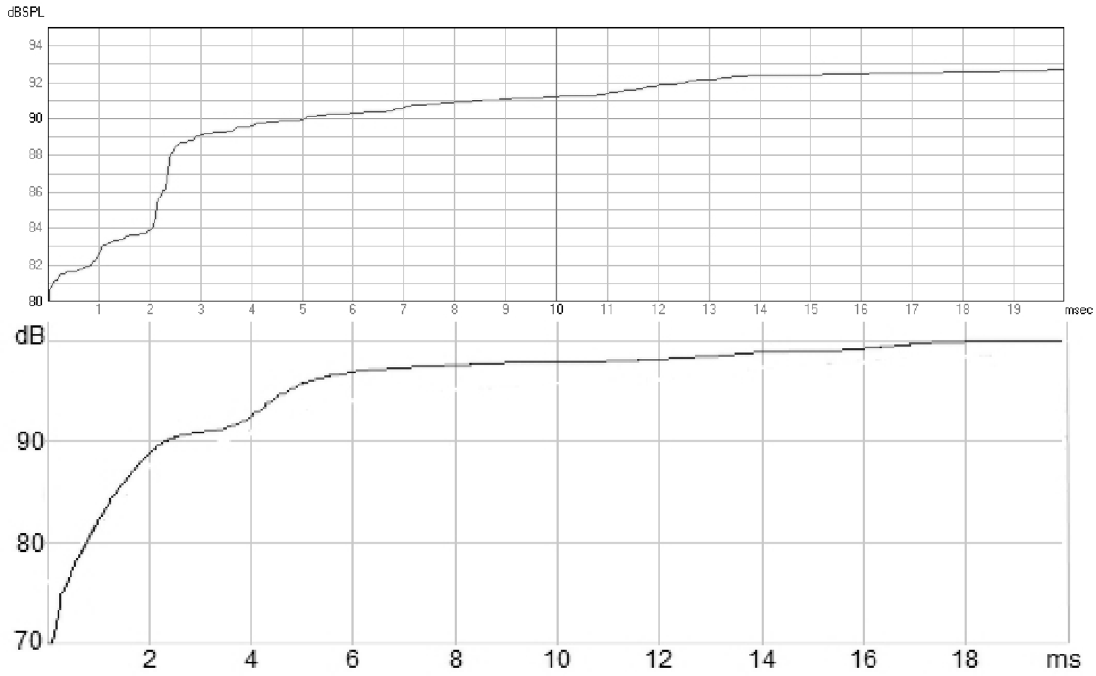


Figure 68: Cumulative energy curve [dB] for loudspeaker position A0 in Studio 31. Top graph presents the measured CEC, the lower graph the calculated CEC.

The measured CEC shows that it is mostly the reflection at 2 ms that builds up the sound in the room with the direct sound. Some weaker reflections contribute up to 14 ms. For later decay times, the curve flattens out.

The calculated CEC has a weak direct sound, the first reflections up to 2 ms and around 4 ms contribute mainly to the sound build-up. Later, the curve is flat and increases slightly around 12 ms. It flattens out at 17 ms.

The following figures show the cumulative energy curve for loudspeaker position A1 for the first 20 ms.

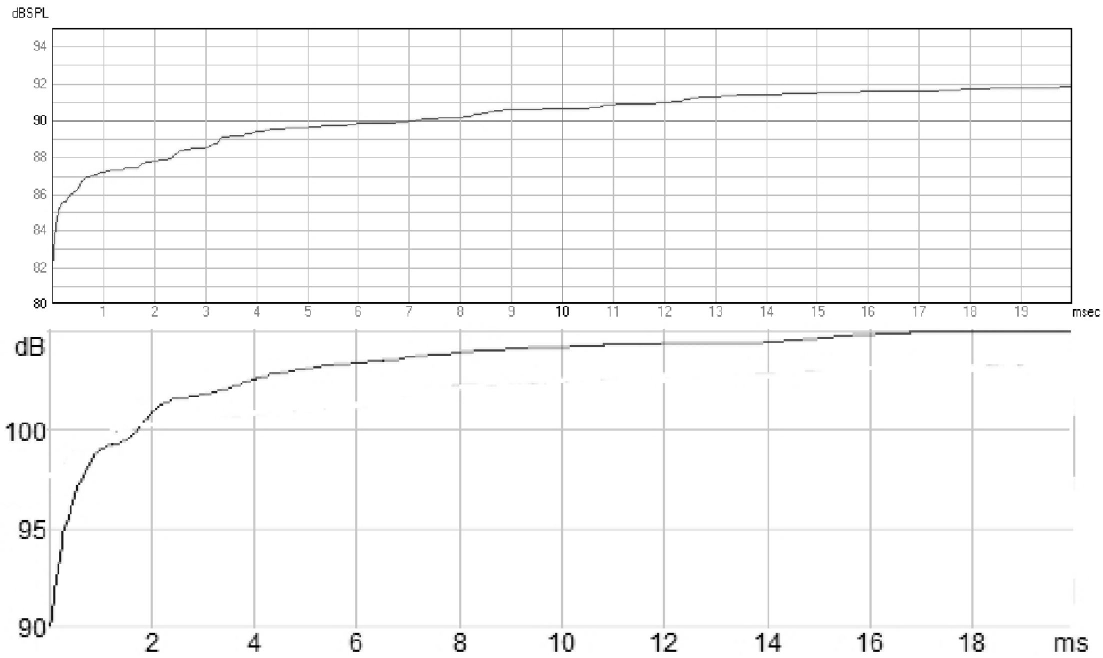


Figure 69: Cumulative energy curve [dB] for loudspeaker position A1 in Studio 31. Top graph presents the measured CEC, the lower graph the calculated CEC.

The CECs by measurement and calculation differ in the first 12 ms.

The measured CEC has some reflections up to 4 ms and around 8 ms that contribute to the sound build-up. But unlike the other loudspeaker position there is not one reflection that contributes very strongly.

For the calculated CEC, it is reflections up to 8 ms that mainly build up the sound in studio 32.

After 12 ms, the measured and calculated curves a have likewise increasing slope.

4.5.5 Frequency response

The following figure shows the measured and calculated frequency response for loudspeaker position A0.

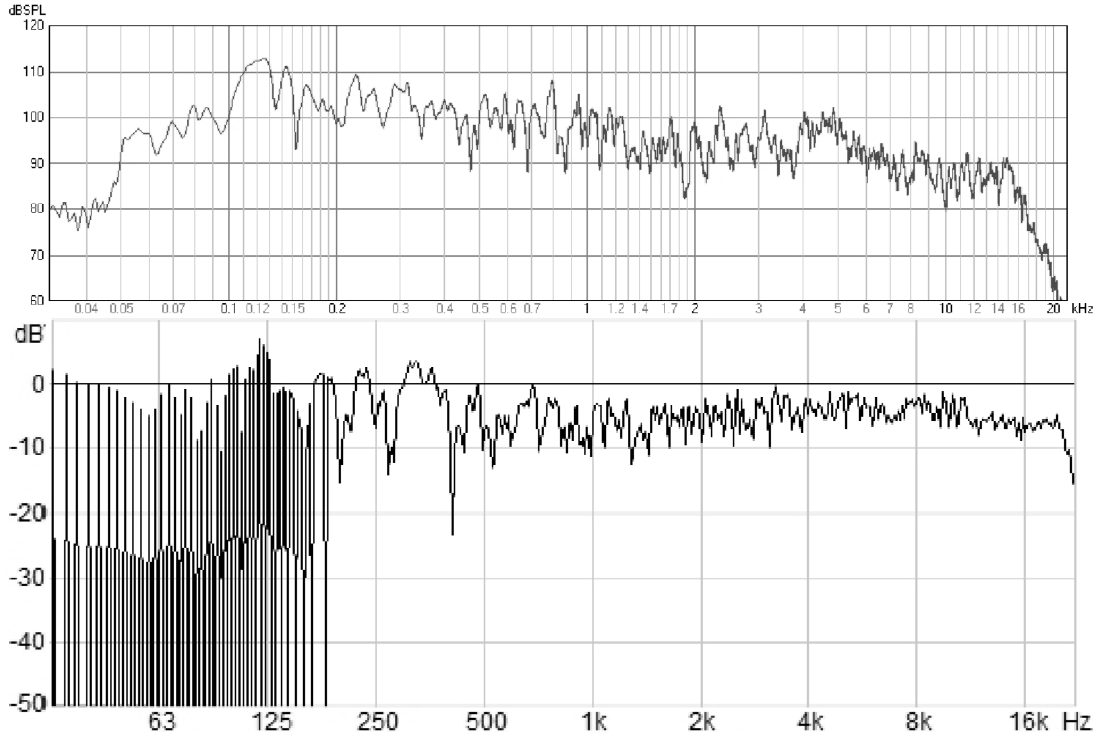


Figure 70: Frequency response [dB] for loudspeaker position A0 in studio 31. Top graph presents the measured FR, the lower graph the calculated FR.

The measured frequency response is flat between 125 Hz and 1 kHz. Frequencies below 125 Hz are low in lvel. For frequencies between 1 and 2 kHz, the response is decreasing. Between 2 and 5 kHz, the FR is flat and decreases down to 16 kHz. For higher frequencies, the FR decreases rapidly.

The calculate FR contains weird results up to 200 Hz. The frequency response is flat up to 18 kHz and decreases rapidly for higher frequencies.

Both frequency responses reveal interference patterns.

The following figure shows the measured and calculated frequency response for loudspeaker position A1.

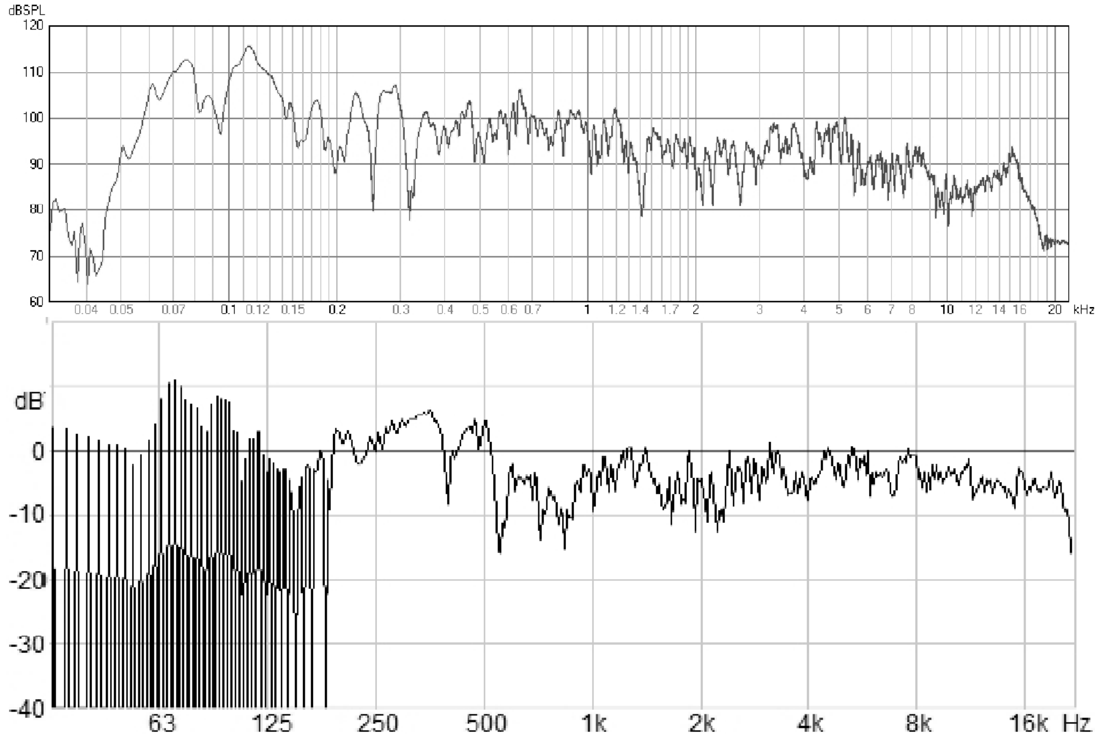


Figure 71: Frequency response [dB] for loudspeaker position A1 in studio 31. Top graph presents the measured FR, the lower graph the calculated FR.

The measured FR is very low up to 50 Hz and increase steeply up to 80 Hz. The FR is flat between 150 Hz and 5 kHz. Higher frequencies are lower in level. There is a peak at 16 kHz. For higher frequencies, the FR decreases rapidly.

The calculated FR contains weird results up to 180 Hz. The FR is flat between 500 and 18 kHz and decreases for higher frequencies.

5 Discussion

In this section, the results are analyzed and explained. The focus is hereby set on comparing measurement and calculation and providing insight on the quality of the studios.

5.1 Studio 12 - LEDE

5.1.1 Comparison between measurement and calculation

- *EDT, T20 and T30*
  Summarizing the results described in section 4.1.1, the following three points need some further analysis:
  - the measurement and calculation correspond well in pattern for T20 and T30
  - the EDT shows larger differences comparing measured and calculated values
  - the calculated values are higher than the measured

  In section 2.3, the Schröder frequency was introduced. The Schröder frequency serves as a limit where the model of geometrical acoustics is valid.
  That means that it is the limit where measurement and calculation should correspond well.

  In the case of the LEDE, the Schröder frequency is calculated to be 125 Hz.

  As seen in the figures 17 and 18, measurement and calculation correspond well in pattern for all octave bands from 125 Hz o 8000 Hz.
  As mentioned in section 3.3), it is instead suggested that geometrical acoustics works well from a limit of $4f_s$, so in the case of the LEDE 500 Hz and *for small rooms such as control rooms and studios typically only the upper octaves 1,2 and 4 kHz will be well predicted* [10].

  However, for the T20 and T30 the model agrees well in pattern from the Schröder frequency.

  EDT is harder to predict because it relies on early reflections. As could be seen in the energy time curve for the two monitors (see figures 21 and 22, there is good correspondence in time for most of the first reflections. However, the level of the reflections differs more between measurement and calculation.

  As said earlier in the method section 3, the EDT is based on a straight line curve fit between 0 and -10 dB. The measurement results from the ETC in figures 21 and 22 that the very early decay is not very linear. This causes the big differences in EDT between measurement and calculation.

The results have shown slightly higher values for the calculated results than for the measured.
In a calculation program, the aim is to model the room as realistically as possible without too many details. Modeling the room exactly as it is with all details would cause very long calculation times and would not necessarily give more accurate values. Instead, all surfaces are provided with absorption and diffusion coefficients.
One difficulty is to find exact determined coefficients for the various surfaces. Often this data is not available and has to be approximated.

For the LEDE, the acoustic consultant that provided me with information for the materials used in the room did not know in detail where and which materials have been used for the LEDE. One difficulty for the implementation of my calculation model was to know where and how many Helmholtz resonators have been used. Additionally, I did not get any measured scattering coefficients for the used diffuser. For the calculation model, I used scattering and absorption coefficients for a similar diffuser.

The higher values for the calculated reverberation times might been caused by the lack of correct information leading to eventually too low absorption coefficients.

At the measurement occasion, many table surfaces were quite chaotic with many papers, cables and other elements. This chaos enhances the diffusion of a surface. The book shelves in the back wall were also filled with in a chaotic way which can increase the absorption.
In the calculation model I did not implement this chaos. So the diffusion and absorption coefficients for the concerned surfaces are not corresponding to reality.

Finally, I had big issues to get information about the loudspeakers directivity. The producer refused to send information. Unfortunately, for such small rooms the directivity is important for the calculation model. In the end, I used approximated directivities.

Looking at the T20 and T30 the calculation model corresponds well in pattern but the higher calculated values were caused by the many obstacles to get accurate information.

- *Impulse response*

  The impulse response is a good tool to get a hint on the appearance of reflections. As described in section 3.4, the IR includes also negative pressure variations and several points that cross the 0 line. It happens easily that only positive pressure fluctuations are judged and not the dips.

  In general, the impulse responses do not correspond very much on the first sight. Only the earliest reflection at 0.5 ms agrees in time.
  The impulse responses for monitor A1 and A2 shows that the calculation does not contain as distinct reflections as the measured IR.

  The right directivity of the loudspeaker is very important for a good correspondence between measurement and calculation in such a small room. This can influence the appearance of reflections and their strength.

  The impulse response includes all frequencies. This is especially problematic for lower octave bands in the calculated IR. It can be expected that there is generally better correspondence for higher frequencies. In the future, it would be interesting to look at the impulse response by octave bands instead.

  In general, it is difficult to compare the impulse responses in the shown scale because the calculated IR is normalized to the sound pressure level at 1 m on axis. However, the SPL at 1 m on axis is constant over all octave bands in my source file.

- *Energy time curve*

  The energy time curves up to around 12 ms correspond very well in time between measurement and calculation for both monitors. In general the calculated reflections are lower in level than the measured ones when compared to the direct sound.

  A ray that hits a surface will be absorbed partly and the remaining part either be reflected diffusely or specular. The calculated values for the ETC might be lower for the first ms because the closest surfaces to the sound source are mainly absorbing surfaces. These surfaces consist of the front wall with absorbers and the absorbing ceiling.
  In the calculation model, the assigned absorption coefficients are very high and reach 90- 100 % absorption after 500 Hz. In theory this means that only 1/10 or less of the rays are reflected from these surfaces.
  In reality, the ceiling for example contains lamps and ventilation making the surface not purely absorptive.

The model of geometrical acoustics does not consider diffraction which affects mostly the lower frequencies. In reality, waves can bend around smaller objects compared to the wavelength and hit a wall behind. In the room model, these reflections would be shielded off. Possible "‘small objects"’ in the room model are the tables next to the console.

For reflections after 16 ms, both calculated ETCs contain several distinct reflections which are around 10 dB higher than in the measured ETC.
The image source model indicated that the later reflections after 16 ms originate from the door.
During the measurement occasion, the chair for the sound technician was placed at its usual position, this means just behind the microphone. The chair-back was higher than the microphone height. This could have provided acoustic shielding from the door reflection.

Still, in general the energy time curves show rather good correspondence in time and shape.

- *Cumulative energy curve*
  The cumulative energy curves for both monitors have a similar shape by measurement and calculation. There are reflections up to 2 ms that cause a steep increase in the sound build-up. Later reflections are not distinctively contributing and cause a linear smooth increase.

  The measured CEC contain more distinct reflections at 0.5 ms and 1 ms for both monitors.
  The calculated CEC is very smooth and shows no distinct slope changes. In CATT, it is possible to evaluate the cumulative energy curve per octave band. The CECs for octave bands 125 Hz and 250 Hz is very smooth in the first 2 ms. The CECs of higher octave bands are more rough in the first 2 ms and show distinct reflections at 0.5 ms and even at 1 ms. Later the CEC is smooth. This behavior corresponds much better to the measured CEC.

  This is an indication that the Schröder frequency is too low of a limit for the accuracy of the model of geometrical acoustics in that case.

- *Frequency response*
  Frequencies below the Schröder frequency are not reliable and are omitted in the discussion.

  The frequency responses from measurement are flat up to 4 kHz and up to 18 kHz from calculation. The frequency response of a room depends on the room itself but also on the frequency responses of the loudspeaker and microphone.

  For the calculation model, the source file contains the sound pressure values at 1m on axis of the acoustical source (frequency response of the loudspeaker in anechoic room). These are flat up to 16 kHz according to the producer. The values are given in octave bands in the source file.

  The measured frequency response shows that the monitors are apparently not able to feed the room with enough sound energy after 4 kHz.

  All frequency responses, both measured and calculated, for the two monitors reveal an interference pattern.

  The superposition of one strong reflection or several equidistant reflections onto the direct sound can create an effect which is called coloration. Coloration causes a change in timbre. This coloration can best be seen in a linear scale on the frequency response. The effect caused by coloration is also called comb filtering because the dips and peaks in the frequency response then appear like a comb.

  In the discussion for the cumulative energy curve, I conclude that only the first reflections are strongly contributing to the total sound build-up in the room.

  The following figures show the linear frequency response for the first 5 ms of the impulse response.

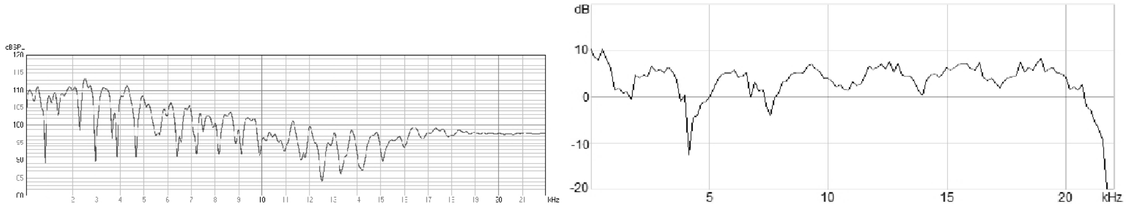


Figure 72: Frequency response [dB] for left monitor A1 in LEDE. Top graph presents the measured FR, the lower graph the calculated FR for the first 5 ms.

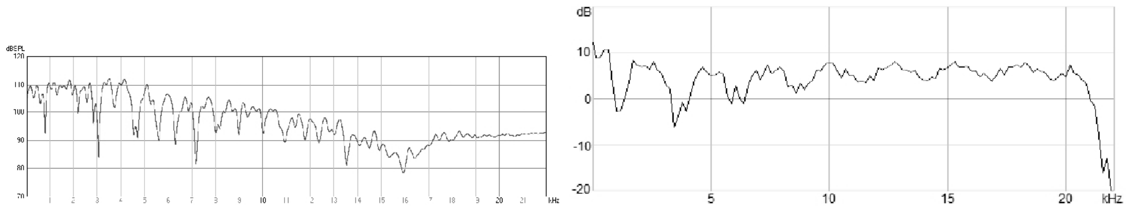


Figure 73: Frequency response [dB] for right monitor A2 in LEDE. Top graph presents the measured FR, the lower graph the calculated FR for the first 5 ms.

In the above figures, the interference pattern or comb filter can clearly be seen for all loudspeaker positions for the measurement and the calculation. The width between two dips does not correspond between measurement and calculation. The calculated dips are wider than the measured ones.

All figures indicate that it is more than one reflection that is causing the interference. The peaks are not perfectly round but have several peaks in one peak which indicates that at least two reflections are involved.

5.1.2 Quality of the studio

The quality of the studio is judged upon the parameters discussed in the paragraphs above. In order to judge the quality, only the results from measurements are considered.

Starting with T20 and T30, the curves are very flat in frequency and take values around 0,25 s. The octave band 125 Hz shows slightly lower value of 0,2 s. The value and flatness of the reverberation times is a very positive property of the LEDE.
EDT differs more from frequency to frequency and takes values between 0,2 and 0,3 s.

In the energy time curve, the most distinct reflections occur at 0.5 ms, 1 ms, 5.5 ms 12 ms, 14 ms and after 18 ms which correspond to the following distances.

Delay time [ms]	Distance [m]
0.5	0.17
1	0.35
5.5	1.9
12	4.2
14	4.8
18	6.2

Table 3: Distinct reflections in LEDE

In order to determine where the reflections are coming from, I use a tool from the CATT software called *Image source modeling* . This tool allows to follow specific reflection paths. Even though the measurement does not correspond exactly to the calculation, it corresponds well enough for reflections up to 10 ms and can still give good hints.

The earlier reflections at 0,5 ms and 1 ms can be associated to the mixing console and are of first order.

The reflection at 5.5 ms originates from a first order ceiling reflection. The reflection at 12 and 14 ms is a second order reflection from both the console and the ceiling.

Reflections after 18 ms originate from the door.
However, the cumulative energy curve shows that only the reflections at 0.5 ms and 1 ms contribute mainly to the sound build-up.

Rod Gervais [13] summarizes the effect of early reflections into three phases:
- Phase 1 (Summing Localization)
Reflections that combine with the original source before about 1 ms cause the sound event to appear roughly half way between the original sound source and the reflection source. This may even result in a slight tonal coloring of the original sound.
- Phase 2 (Localization Dominance)
The original sound and a reflection occuring between 1-10 ms combine in a way that the first signal, the original sound, appears louder.
- Phase 3 (ISD)
Reflections that occur after 10 ms can be perceived as two different sound sources (see Haas effect in section 2.2).
So, the two reflections at 0.5 ms and 1 ms are Phase 1 reflections, the ceiling reflection at 5.5 ms is a Phase 2 reflection and the reflections at 12 ms, 14 ms and 18 ms are Phase 3 reflections.

The following figures show the measured frequency response of the first 2 ms.

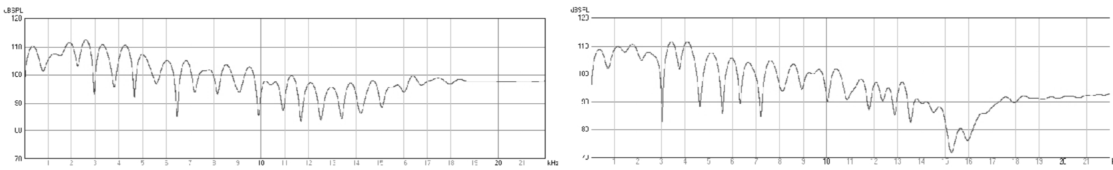


Figure 74: Frequency response [dB] for left and right monitor in LEDE. Left graph presents the left monitor, right graph the right monitor for the first 2 ms.

For the two monitors, both reflections at 0,5 ms and 1 ms contribute to the comb filter This corresponds to the description of Phase 1 reflections.

A large mixing console with large flat surfaces tends to dominate the acoustic response of a small room. According to Newell [7] even when using monitors with an extremely flat response, there is little chance of achieving a flat response at the listening position.

Even though these colorations could be measured in the LEDE room, it does not automatically mean that they are also perceived by the technician. It much depends on the delay time and the level of the maxima [5]. The following figure shows the sensitivity to comb filter, hence when the coloration gets audible.

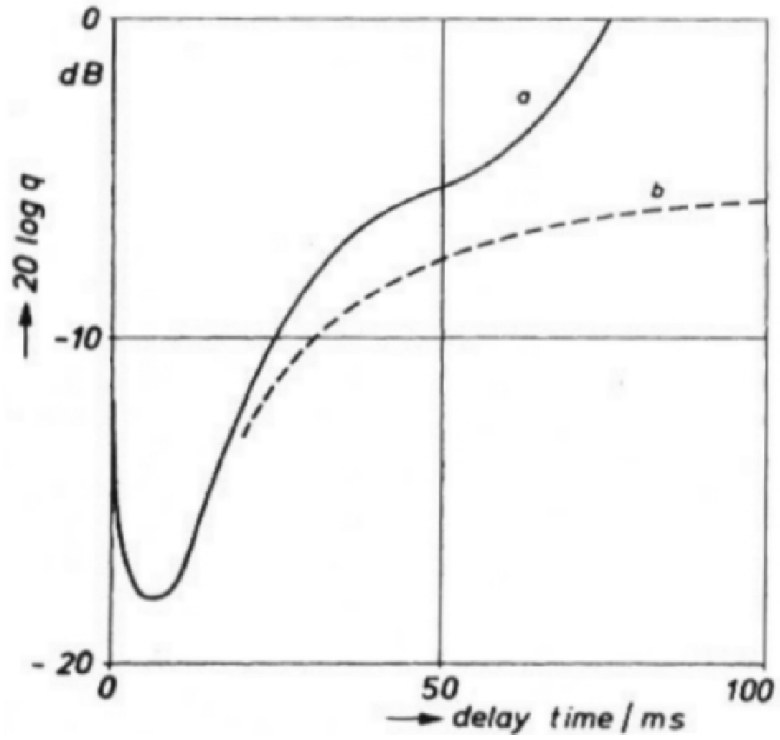


Figure 75: Comb filter sensitivity. a) for a single reflection, b) for a succession of reflections

For my purpose, only curve a) is interesting as the impulse response or energy time curve do not reveal a regular succession of reflections.

Being above the curve means that the coloration is audible. The frequency response for 2 ms shows that two dips are around 900 Hz spaced from each other. This space is defined as $1/t_0$ where t_0 is the delay time. So for 900 Hz, the delay time corresponds to 1 ms. At 1 ms the reflection has to be around 15 dB lower than the direct sound so that the coloration is inaudible.

From the energy time curves of the two monitors, one can read that the first two reflections are approximately 10 dB lower than the direct sound.
This indicates that the coloration could cause a change in timbre in the LEDE.

It is a typical issue of control rooms that the mixing console. In general, it is desirable to have a small mixing console.

In the case of the LEDE, the monitors are placed free-standing above the meter bridge.The following figure shows the influence of the reflection from the mixing console on the transient response of a loudspeaker placed on the meter bridge [7].

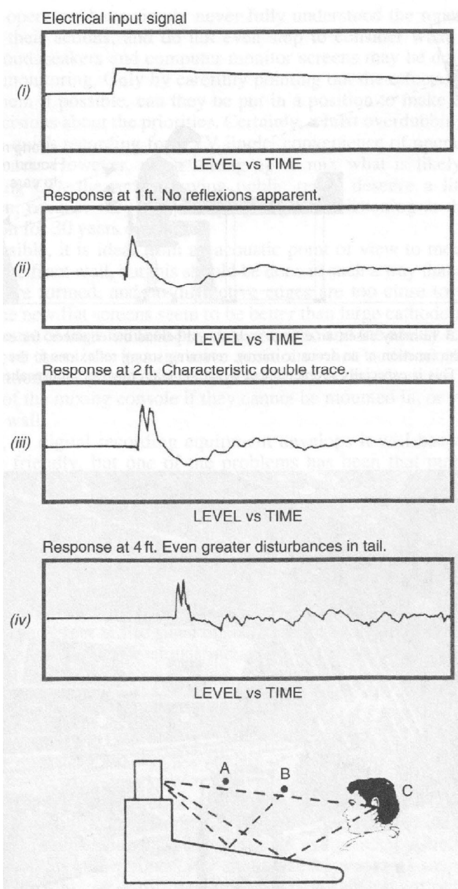


Figure 76: Effect of reflections from top surface of mixing console from loudspeaker placed on the meter bridge.

Point A corresponds to the plot in (ii) for 30 cm, point B to (iii) for 60 cm and point C to (iv) for 120 cm. Newell wants to show with this figure that the reflections are apparent at position B and C causing also disturbance in the tail of the plot. The LEDE case corresponds to point C.

He states for this point that neither coloration nor transient smearing is beneficial for the monitoring quality. Comparing with the impulse response for the two monitors in figures 19 and 20, the plot in (iv) looks very similar.

The mixing console that was used in the LEDE is one of a kind that Newell criticizing [7]. The problem is that it has a closed back from the meter bridge to the floor. The parallel vertical space between the console and the wall can cause resonances.
In order to reduce the effect, the studio technician clearly made an effort and leaned loose absorptive material against the back of the console. Even though the lower part of the front wall is absorptive, thick cloth covers it additionally.

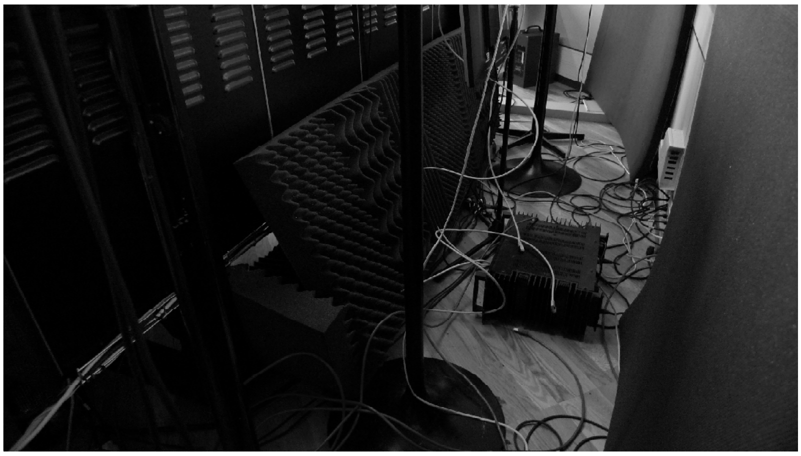


Figure 77: Back wall of the mixing console. Photo: Tina Roth

Also, the figures of the frequency responses reveal a dip at 80 Hz for both monitors as mentioned in the results for figures 25 and 26.

On Genelecs webpage [14], the critical issue of bass response in rooms is described. This poor bass response is caused by walls or other boundaries that are close to a free-standing loudspeaker.
When the total distance traveled by the reflected sound from this wall is half a wavelength of the direct sound, it destructively interferes with the direct sound and causes a dip in lower frequency, in figures 25 and 26 at 80 Hz. The boundary that corresponds in distance to that frequency is the big tilted window in the front wall.

Unfortunately, this big tilted window is an important contact to the studio in order to enhance communication between performers in the studio and technicians in the control room.

5.2 Surround studio

5.2.1 Comparison between measurement and calculation

- *EDT, T20 and T30*

  The figures 27, 28 and 29 reveal that the EDT shows no correspondence for the three monitors. As said earlier for the discussion of LEDE 5.1.1, the EDT is based on a straight line between 0 and -10 dB. It is much harder to predict right.

  Also whereas T30 for example is a global measure, EDT describes much more local acoustic conditions.

  T20 and T30 agree better than EDT. For T20 and T30 the octave bands 250 Hz and 500 Hz are slightly underestimated in reverberation time.
  The surround studio was designed by a consultant that I did not have contact with. The choice of the materials for my absorption file was inspired by the choice of material for the LEDE. The consultant working with LEDE and the other studios stated that the materials chosen for the surround studio were similar.

  The absorption coefficients for the absorptive wall panels are adapted for absorption material that is mounted with space from the wall, the space being filled with mineral wool. This gives higher absorption coefficients in the lower frequencies up to 500 Hz.
  As the reverberation times are calculated too low for these frequencies, I guess that the material was mounted closer to the wall than in the LEDE.

  Higher frequencies on the other hand were overestimated. A possible explanation could be that the room is more diffusive in reality enabling more sound waves to enter the present absorption material. The mathematical diffuser in the back wall is only an approximation in the calculation model and does not represent the real randomness of reflection in reality.

  However, the differences in frequency are not as big as for the T20 and T30 in the LEDE. The Schröder frequency is 123 Hz in the surround studio. All frequencies from the calculation model give good agreement to the measurement.

- *Impulse response*

  Most distinct reflections in both calculation and measurement appear in the first milliseconds. Measurement and calculation seem to be shifted in time. This will be further discussed for the energy time curve.

  The general pattern of the impulse responses corresponds well for all three monitors. The calculated impulse response is normalized to the sound pressure level at 1 m on axis which makes it harder to compare measurement and calculation.

  However, there are only few reflections after the initial reflections that can be seen in both measurement and calculation. The strength of later reflections in the impulse response is low.

- *Energy time curve*

  All calculations for the three monitors are shifted in time compared to the measurements. For monitor A1 and A2 the calculation is shifted by 0.5 ms or a bit more, monitor A3 by less than 0.5 ms.
  This indicates that the placement of the microphone in the room during measurement occasion and in the calculation model is not the same. If the microphone position is in the middle of the room for the measurement for example, the microphone position for the calculation is shifted towards the monitor A3.

  The first reflections up to 0.5 ms for measurement and 1 ms for calculation are 10 dB lower than the direct sound for all three monitors. So here, the model and reality corresponds well.

  Later reflections are 5 dB less strong in the calculation model than by measurement for all three monitors.
  The maximum ray split in the calculation model is 2. This means that every time a ray hits a reflecting surface, the ray is split into new rays. This counts only for rays up to second order. Higher order rays are determined randomly from the scattering coefficients without split-up.
  In reality there is split-up also for higher orders creating an infinite number of rays that all add up.
  The walls close to the loudspeaker (hence earlier reflections) are mainly absorptive whereas later reflections will originate from reflections surfaces.
  This could explain why later reflections in the calculation model are lower in level than by measurement.

  All three monitors reveal reflections just after 3 ms , the measurement with monitor A3 shows a strong reflection at 9.5 ms. The reflection at around 3 ms originates from the ceiling whereas the later reflection from monitor A3 is hard to determine.

- *Cumulative energy curve*
  It is mainly the first reflections up to 1 ms that contribute to the total sound field in room when looking at the CEC by measurement.
  As for the LEDE, this contribution takes longer for the calculated CEC. When looking at individual octave bands, it is mainly octave bands 125 Hz and 250 Hz that cause the slower steepness until reaching the final level.
  Additionally, the shift in time contributes as well.

  The total value by calculation is around 20 dB higher than the measured total value. This means that the gain is higher for the calculation than for the measurement. This can not be seen in the impulse response or energy time curve as they are normalized to the sound pressure level 1 m on axis.

  These first reflections that are contributing most to the sound build-up are reflections from the console.
  Later reflections have only minimal effect by measurement and none by calculation.

- *Frequency response*
  The frequency responses differ much between the different monitors and from measurement and calculation.
  For the frequency responses to agree it is crucial that the gain corresponds over the whole frequency range. As mentioned for the CEC this is not the case for the surround studio.

  The frequency response by measurement is flat up to 2 kHz and decreases after that. The frequency response by calculation is flat between 1 kHz and 18 kHz and decreases for higher frequencies.

  The calculated frequency response corresponds more to an ideal behavior of the used loudspeaker. Real measurements show that the loudspeaker does not fulfill the theoretical expectations.

5.2.2 Quality of the studio

The surround sound studio has a very flat reverberation time as seen in the measures T20 and T30. The early decay time differs more in frequency.
Still, the reverberation times are around 0.2 s which is very short and gives the impression of a dry room. This short reverberation time is good for a control room that is reserved for speech.
Also it is good for the studio's quality that the EDT and T20 and T30 are in the same range. This indicates an uniform decay.

The impulse responses and the energy decay curves states that the most dominant reflections occur in the first millisecond. These originate from the console. The cumulative energy curve indicates that it is mainly these that contribute to the sound build-up in the room.

They are 10 dB lower than the lower sound so the Haas effect does not occur in this case. According to Gervais, they could lead to a tonal coloration (Phase 1 reflections).

The following figures show the frequency responses on a linear scale of the first 1 ms for all three monitors:

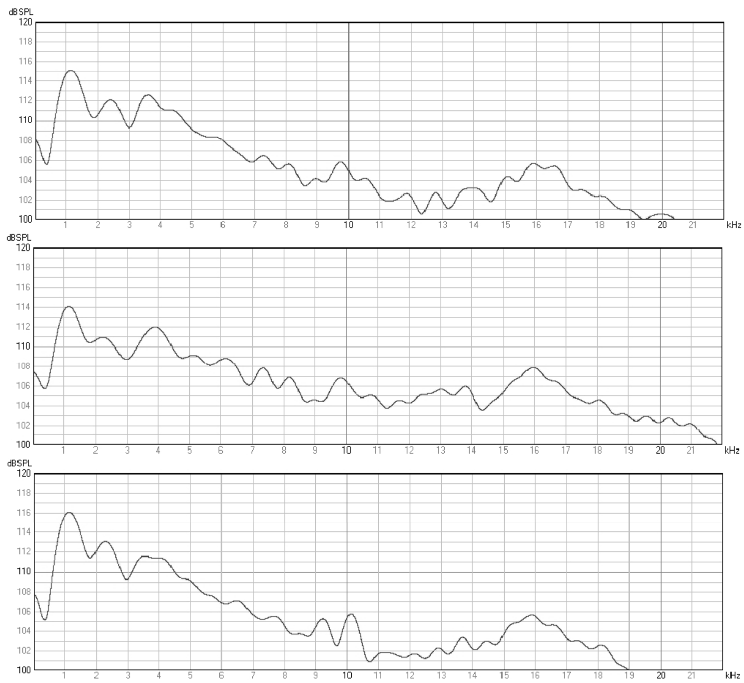


Figure 78: Frequency response [dB] for monitors A1 (top graph), A2 (middle graph) and A3 (lower graph) in surround studio. Linear scale

Looking at these figures a slight comb filtering can be seen but it is not as severe as for the LEDE (see figure 74). The mixing position is not affected of coloration due to the console. Compared to the LEDE, the console in the LEDE was much closer to the monitors as they were placed on the meter bridge.

The monitors in the surround studio are integrated into the wall.

Another benefit of this placement can be seen in the lack of dip in the low frequency range. Only monitor A2 has a weak dip at 80 Hz. This can be caused by the closed back of the console. Only monitor A2 is affected as it faces the console-back straight and not angled as the other monitors.

In total, the best quality of this studio is that there are no dominant later reflections and that the strong early reflections do not cause coloration of the sound at the mixing position.

5.3 Studio 42

5.3.1 Comparison between measurement and calculation

- *EDT, T20 and T30*
  As seen in figures 42 and 43, the shape of the EDT corresponds well from 2 kHz between measurement and calculation for both loudspeaker positions. The calculated values are slightly higher than the measured.
  For T20, there is good correspondence from 500 Hz on for both loudspeaker positions.
  For T30, loudspeaker position A1 corresponds better than A0 with agreeing levels from octave band 500 Hz.

  The Schröder frequency was calculated to be 155 Hz in Studio 32. The results indicate that the Schröder frequency is a too low limit for a reliable calculation model with geometrical acoustics. Studio 42 is a very small studio. The calculation model agrees well from 3 times the Schröder frequency for T20 and T30. This corresponds better with the findings of Bengt-Inge that are mentioned in the manual [10].

  Loudspeaker position A1 shows better correspondence for T20 and T30 than loudspeaker position A0. This could be due to the loudspeaker position. Loudspeaker position A1 was placed in the corner of the room. In this way it excited the room better than the placement for A0.

  Another interesting finding is that the lower frequency band is calculated much higher in T20 and T30 than by measurement. This could indicate the use of bass traps / Helmholtz resonators in Studio 42. As mentioned in section 3, I did not have information regarding bass traps and did not implement them in my room model.

- *Impulse response*
  The impulse response for the loudspeaker position A0 does not show much correspondence. The impulse response corresponds better for loudspeaker position A1.

  The direct sound of the measured loudspeaker position A0 is much lower than for loudspeaker position A1. The IR of loudspeaker position A0 shows no distinct reflections after 3 ms. The low direct sound level is not as strong to excite the room sufficiently hence reflections are also weak.

  As the loudspeaker position A1 is in a corner of the room with direct sight to the listening position, the direct sound is stronger and the sound energy is directed towards the room. Loudspeaker position A0 was placed at the corner between door and window, the corner pointing inside the room. The loudspeaker was also slightly shielded by the studio table and the computer screens. In reality, the sound was probably diffracted at the corner, the table and the screens before reaching the receiver. Diffraction is not modeled in my calculations which might explain the weak correspondence for loudspeaker position A0.

Especially the early reflections up to 8 ms correspond well in time for loudspeaker position A1.

- *Energy time curve*
  The energy time curve does not differ much from the analysis for the impulse response. The ETC for loudspeaker position A1 shows better agreement than position A0.

  It is harder to distinguish strong reflections in the measured ETC for both loudspeaker positions. The strength of several reflections is only 5 dB less than the direct sound.

  The calculated ETC for both loudspeaker positions shows strong peaks at 9 ms for A0 and at 7 ms for A1 . These reflections are around 10 dB lower than the direct sound. All other reflections are at least 20 dB lower than the direct sound.

  The ETC by calculation contains reflections that are weaker than the direct sound when compared to the measurement. This is due to the fact that the direct sound by calculation is stronger than by measurement. The computer screens on the table are shielding reflections from the receiver position that would have bend otherwise.

- *Cumulative energy curve*
  For the cumulative energy curve, I could see better agreement for loudspeaker position A0 than for A1. The slopes behave similarly by measurement and calculation for loudspeaker position A0.
  Reflections involved in the sound build-up are more distinct in the measured CEC than in the calculated CEC.

  The sound build-up with loudspeaker position A1 takes more time and more reflections are involved by measurement than by calculation.

  The CEC shows that it is not enough to have a good correspondence in time. The ETC for loudspeaker position A1 shows that the reflections do correspond in time but are much weaker in level from the calculated room model. In respect to that, they do not contribute as much to the total sound build-up in the room which makes the curve flatter. Hence, measured and calculated CEC agree less.

- *Frequency response*
  The loudspeaker is not able to feed the lower frequencies with enough power, hence the low levels up to around 63 Hz for both loudspeaker positions seen in the measured frequency response. At 18 kHz there is another dip also caused by the used loudspeaker.

  The calculated FR on the other hand gives a more ideal picture of the room with more flatness and less distinct interference pattern.
  As explained for the previous rooms, the frequency response up to the Schröder frequency is not reliable.

  The results for the frequency response do not correspond between measurement and calculation.
  This is mainly caused due to the source properties (directivity, gain, position) used in the calculation model.

5.3.2 Quality of the studio

The EDT is quite flat for the higher frequencies, for the lower it fluctuates more. T20 and T30 are linearly decreasing from the lower to the higher frequencies and take values between 0.3 s and 0.18 s. The reverberation time is short which is a good quality for a studio. However, the fact that the lower frequency band has longer reverberation time could cause the room to seem bassy as the lower frequencies will need more time to die out.

The ETCs for both loudspeaker positions contained a lot of reflections that are only 5 dB weaker than the direct sound. The plots for the LEDE (figures 21 and 22) and the surround studio (figures 33, 34 and 35) show that the reflections are much lower than the direct sound.
The boundaries of studio 42 are less treated which can be seen in the amount and strength of dominant reflections.

The CEC shows additionally that a lot of reflections, also later ones, contribute to the total sound build-up.

The chosen loudspeaker positions do not represent in any way how the studio is used. The monitors used in the studio are placed on the table (see figure 3.1.3). The reflections stated above might not be the reflections that can disturb the technician. Still, I found it interesting to see where the most dominant reflections might come from when reaching the receiver position.

The CATT tool *Image Source Model* showed clearly that a lot of reflections in the first ms after the direct sound come from the window behind the table and the ceiling. Reflections around 7 ms originate from the cupboard that is on the left hand wall next to the table.

As for the LEDE, I can imagine that the table itself is causing an early reflection as the monitors are placed right above the table and it is a big, flat surface.

The frequency response shows a clear interference pattern for the chosen loudspeaker positions.

A weakness of this studio are the numerous windows that are installed in the studio. Only one window serves as a visual contact towards the adjacent studio so that one of them could be used as a control room. The remaining windows are facing the corridor. They are only installed to have insight into the studio and light intake. Unfortunately, they cause reflections that deteriorate the studio quality.

During the four occasions I visited the Kanalhuset and Studio 42, the program presenter wore headphones every single time. As it is a radio broadcast, it makes sense to use head-

phones in order to avoid feedback. When a microphone is turned on in a radio studio, the monitors automatically mute. The only way to monitor the broadcast in this situation is by using headphones.
The headphones excuse the poor design with several windows in the studio.

The monitors on the table are probably not used that much.

For radio broadcasting, the aim of the studio is not to produce excellent sound for high developed hifi-systems. It is rather to monitor the sound in a way that it sounds good in an average living room for domestic purposes.

5.4 Studio 32

5.4.1 Comparison between measurement and calculation

- *EDT, T20 and T30*

  As for the other studios, EDT deviates the most between measurement and calculation. The two loudspeaker positions give different curves by measurement. Whereas EDT by loudspeaker position is flat, EDT by loudspeaker position A1 is decreasing in frequency.

  The impulse response in figure 54 contains a weak direct sound by measurement for loudspeaker position A0.
  The flatness of the curve seen for the EDT is not reliable. It is more realistic that the EDT follows the same pattern as T20 and T30 for loudspeaker position A1: decreasing in frequency.

  EDT calculated with loudspeaker position A0 agrees well in pattern from octave band 1 kHz but the calculated EDT is shorter.

  As it is more difficult to get good agreement for EDT, it is better to focus on T20 and T30.

  T20 and T30 are much alike for both loudspeaker positions respectively by measurement and calculation.
  Octave band 125 Hz has a much longer calculated reverberation time than higher octave bands.
  This indicates the use of Helmholtz resonators that are tuned for this octave band or a lower octave band that would affect 125 Hz too. As well as for studio 42, the acoustic consultant could not provide me with this information.

  In general, T20 and T30 agree well from 1 kHz for loudspeaker position A0 and 2 kHz for loudspeaker position A1 on.
  The Schröder frequency of this studio is 187 Hz. Studio 32 has the lowest volume of all the studios. Here, Bengt's statement that *for small rooms such as control rooms and studios typically only the upper octaves 1,2 and 4 kHz will be well predicted* agrees well with the results from figures for T20 and T30 in 52 and 53.

- *Impulse response*

  The impulse responses in figures 54 and 55 show a weak direct sound by measurement for loudspeaker position A0 and a non-existing calculated direct sound for loudspeaker position A1.

The weak direct sound that was measured for loudspeaker position A0 is probably caused by the shielding of the table. The table position was adjusted for a standing person and the loudspeaker placed on the floor. The loudspeaker might have been oriented in an unfavorable angle towards the receiver so that a part of the sound was reflected on the bottom of the table. This would cause a weaker direct sound.

The ray tracing option of the image source model shows that the direct sound from the source reaches the receiver in a straight line in the calculation model. The ray passes just over the edge of the table.

The first reflections in the first millisecond correspond between measurement and calculation. The reflection is a floor reflection. The measured reflection at 2 ms (2.3 ms in calculated IR) originates from the big window behind the listening position. The shift in time corresponds to around 10 cm and could just be caused by a different hitting point of the specular reflection in the calculation model or a slightly shifted loudspeaker or microphone position.

The distinct reflections in the calculated IR is a first order reflection at 6 ms and second order at 9 ms associated to the big tilted window. The measured direct sound is too weak to cause distinct reflections after 5 ms.

For loudspeaker position A1, the direct sound by measurement is stronger than for the previous position. On the other hand, there is no direct sound for the calculated IR.

The results do not agree at all which is not extraordinary given that the sound source is completely shielded off from the receiver in the calculation.

- *Energy time curve*
  The energy time curve does not add any new information.
  The direct sound that is measured with loudspeaker position A0 and calculated with position A1 is too weak and deteriorates the agreement of the results.
- *Cumulative energy curve*
  The cumulative energy curves do not correspond well between measurement and calculation as could be expected from previous results.

  The calculated CECs are flat from 4 ms and no later reflections contribute strongly to the sound build-up.
  The measured CECs on the other hand contain frequencies in the first 4 ms that are mainly contributing. Later, the slope is increasing and flattens out around 18 ms.

- *Frequency response*

  The frequency responses do not correspond well between measurement and calculation which agrees with the previous results.

  There are several strong negative interferences that cause dips in the measured FR. The calculated FR has much weaker dips. Also, the calculated FR is flatter over a larger frequency range than the measured FR.

  In reality, the loudspeaker is not able to feed frequencies lower than 60 Hz and higher than 5 kHz with enough power which can be seen in lower levels for these frequencies.

  The Schröder frequency is 187 Hz for studio 32 which can be seen very well in the FR. The results below 200 Hz are not reliable for both loudspeaker positions.

5.4.2 Quality of the studio

The evaluation of the studio quality is restricted to loudspeaker position A1 as the direct sound is stronger and the results more reliable.

EDT, T20 and T30 are decreasing in frequency. As discussed for studio 42, also studio 32 runs the risk that the room may sound bassy.

The strongest reflection occurs at 3.5 ms. According to the energy time curve, this reflection is almost as loud as the direct sound. The cumulative energy curve adds that it is the direct sound, the floor reflection and this reflection that contribute mainly to the sound build-up in the room.

The reflection at 3.5 ms is associated to the big tilted window behind the listening position.

In general, the energy time curve shows an overall high level of sound where several reflections are only 15 dB lower than the direct sound.

Studio 32 has two big purely reflecting surfaces that are facing each other. The tilted window omits flutter echoes but there are a lot of reflection build-up that deteriorates the studio quality.
The frequency response for loudspeaker position A1 shows an interference pattern. This is mainly caused by the reflection at 3.5 ms which can be seen in the following figure showing the frequency response of the first 4 ms.

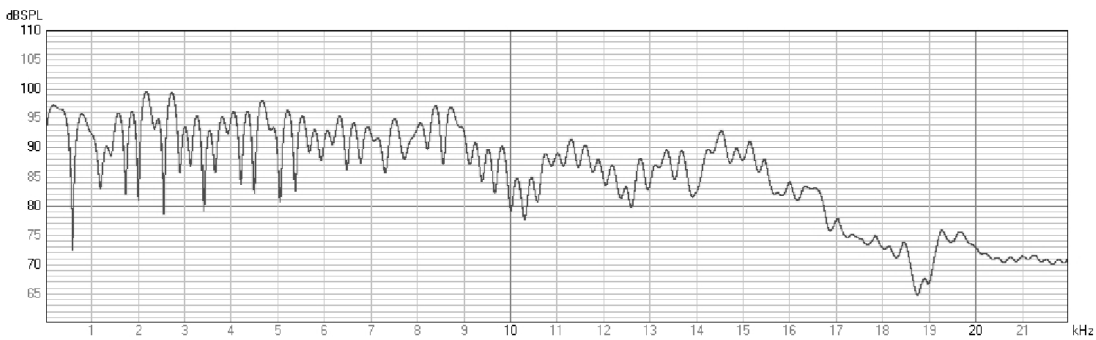


Figure 79: Frequency response [dB] for loudspeaker position A1 in studio 32 for the first 4 ms.

The combs are clearly seen in the above figure.

However, as for the previous studio 42, the program presenter used headphones during my visits to Kanalhuset. It can be expected that the small monitors on the table are not used very often.

To summarize the qualities of the studio, the two facing windows are not favorable for the sound environment that the program presenter experiences at the listening position. The ceiling is lower just above the table which improves the situation slightly.
The windows are not facing towards an adjacent studio or control room. They only face corridors on each side and are not necessary for radio broadcasting as they do not serve as a contact possibility. It is unfortunately not really comprehensive why they have been designed so big.

On the other hand, the studio is a studio for radio broadcasting where the program presenter controls the sound by himself, probably wearing head phones during the whole program. So in this context, the studio works just fine.

5.5 Studio 31

5.5.1 Comparison between measurement and calculation

- *EDT, T20 and T30*
  The figures for EDT, T20 and T30 for loudspeaker position A0 show that they do not correspond between measurement and calculation.

  The calculated impulse response in figure 64 for this loudspeaker position contains no direct sound at all. The calculated results for loudspeaker position A0 are not reliable after all.

  Loudspeaker position A0 was placed in the corner of two windows in front of the table. The table and the computer screens probably shielded the source from the receiver in the calculation. In reality, the sound waves would bend around the object's edges.

  Loudspeaker position A1 is placed in the corner next to the cupboard behind the receiver position.
  EDT shows no correspondence at all. As said earlier, is is hard to predict the early decay time right.

  T20 and T30 showed much better correspondence. T20 is affected by the surrounding absorbing surfaces and is slightly lower than the measured values. T30 is longer for frequencies above 1 kHz.

  The Schröder frequency for studio 31 is 151 Hz. At the first sight, it seems that there is good agreement over all octave bands. But it is hard to judge the effect of the Schröder frequency as T20 and T30 are calculated lower respectively higher compared to the measurement.

- *Impulse response*
  As just said above, the impulse response by calculation contains no direct sound as it is shielded off by the table and the computer screens.

  However, there are some reflections in the the first 5 ms that are corresponding. These reflections can be associated to the ceiling and the floor.

  The measured and calculated IR for loudspeaker position A1 are agreeing in the first 5 ms with some corresponding peaks and dips. The surfaces that cause these reflections are the cupboard and the floor.

Later reflections are very low for the calculated IR. The loudspeaker was placed in a corner that is surrounded by absorptive materials (walls and ceiling). A lot of the sound energy disappears in the absorption material in the calculation model.

I chose the loudspeaker positions in studio 31 in order to excite the room best, that means in corners. The placement caused shielding for one loudspeaker position and too much absorption for the other. The placement of loudspeaker positions should be improved in the future in order to get more reliable and corresponding results.

- *Energy time curve*
  The energy time curve picks up the conclusion drawn for the impulse response. There is some correspondence in the first 5 ms.
  Loudspeaker position A0 corresponds less than A1.

  The reflection levels compared to the measurement are much lower by calculation. For A0, this is due to the weak direct sound. For A1, it is due to the ideal absorption in the corner.

- *Cumulative energy curve*
  The CECs for loudspeaker position A0 do not show much correspondence as expected from previous results. The CECs for loudspeaker position A1 basically only correspond after 12 ms where the slopes are increasing in a likewise angle.

  For the calculated CEC, it is mainly the direct sound and a stronger reflection at 2 ms that build up the sound in the studio. However, several weaker reflections contribute all the way and cause an increasing slope.

  The measured CEC corresponds in the way that reflections up to 8 ms contribute mostly. There are several weaker reflections and not a distinct reflection that build up the sound with the direct sound.

- *Frequency response*
  Results below the Schröder frequency are not reliable in the calculated FR.

  Whereas the calculated FR is rather flat up to 18 kHz, the measured FR is flat in a much narrower frequency range and fluctuates much more.

  The source file should be improved in order to match the measured and calculated results better. A slight shift in positions, the directivity and gain are all factors that influences the frequency response.

5.5.2 Quality of the studio

Studio 31 has the same tendency as studio 42 and 32 when it comes to octave band 125 Hz: the reverberation time is longer than for higher frequencies.

The curves are not uniform and differ much in frequency and between the parameters. Although the reverberation time is very short which is a good quality of the studio, the fluctuations in frequency can create a sound decay that is unpleasant.

The energy time curves reveal that there are some early reflections up to 5 ms that are only some dB lower than the direct sound. The cumulative energy curves show that it is these that contribute most to the sound build-up in the room.

For loudspeaker position A0, these reflections are caused by the windows and the floor. For loudspeaker position A1, the cupboard is the reason.

The cumulative energy curves are increasing in the first 20 ms which means that several later reflections are building up the sound. These reflections can be caused by the windows that reflect the sound specular.
40 % of the rooms surfaces are covered with windows. None of these windows serves as a contact possibility and seem unnecessarily big to me.

During measurement occasion, some absorption material was loosely leaned towards some windows.

Figure 80: Loose absorption material in studio 31. Photo: Tina Roth

The frequency responses indicate the presence of coloration in the room.

However, as for the previous broadcasting studios the program presenter wears usually headphones which makes the room's properties less important.

6 Conclusion

The aim of this Master thesis is to investigate sound reflection patterns in studio and control rooms. For this purpose, measurements and calculations in five studio and control rooms are compared. Furthermore, the quality of the studio is judged upon the measured results.

The study of reverberation times in the studio and control rooms has shown that for studios with larger volume (Studio 12 - LEDE, Studio 31) or studios that are well designed for acoustical purposes (Surround studio) the Schröder frequency is corresponding to the frequency limit from which measurement and calculation correspond well.

For smaller studios that are less acoustically developed (Studio 32, Studio 42), the Schröder frequency is a too low limit and agreement between measurement and calculation rather occurs for 4 times the Schröder frequency.

A room model in a calculation program is an approximation of reality. The aim is to find a good balance in detail so that the calculation time is kept short and the model gives realistic results. The surfaces in a calculation model are assigned with absorption and scattering coefficients.

For small rooms such as the studio and control rooms investigated in this thesis, it is crucial to have correct data for all materials. Furthermore, the source file is important for good correspondence of results. The source position, directivity and gain matter much in these small rooms.

Impulse response, early decay curve and cumulative energy curve are all tools to investigate reflections. The impulse response shows the dominant reflections most clearly. However, it is easy to only focus on positive pressure fluctuations but also negative pressure fluctuations should be considered. In the early decay curve which plots the impulse response on a dB scale over time, the level difference between direct sound and reflection are read. Once knowing the strongest reflections, the cumulative energy curve helps to judge how important they are for the sound build-up of the room.

The frequency response then gives a picture of the sound level per frequency. Most rooms reveal interference patterns in the frequency response. Information in the early decay curve about the reflections strength compared to the direct sound can help to judge if the reflection causes psychological perception effects such as Haas effect or coloration.

The LEDE and the surround sound studio show rather good correspondence between measurement and calculation for all parameters apart from the frequency response.

The other studios show good correspondence when the direct sound by neither measurement or calculation is reduced or omitted by shielding of the receiver from the sound source.

For future investigations, careful preparation of a measurement is desirable. When placing the own loudspeaker in the broadcasting studios, I only chose corner positions because I wanted to excite the room the most. I did not pay attention to an eventual shielding of the receiver.

The results mostly correspond up to 5-10 ms depending on the room. The calculations usually contain more distinct reflections for later sound arrivals. The measured energy time curves contain no such reflections in most of the rooms.
The calculation is based on algorithm 1 with a max ray split up order of 2. Rays that are of higher order than two, are not split up deterministically. Instead, the reflections are determined randomly from the scattering coefficients. This can cause more specular reflections also for higher orders. The CATT tool "‘image source model"' reveals several higher order reflections that cause strong later peaks in the impulse response.

In reality, the design of the rooms and choice of material omit strong reflections after 10 ms.

However, the cumulative energy curves shows that for the three broadcasting studios several reflections arriving up to 20 ms after the direct sound are involved in the sound build-up in the studio. The slope is increasing in time.

The surround sound studio is the studio that has the flattest cumulative energy curve and where no reflections after 2 ms contribute to the sound build-up. This corresponds well to the calculated results.

The frequency responses show least correspondence between measurement and calculation. Here, the source file in the calculation model is crucial to obtain results that agree with reality.

As I could not get hold of accurate directivity data from the producers, I used directivity files from similar loudspeakers. In the future, the measurements should be performed with loudspeakers where the directivity is well known or can be measured.

The quality of the studios is judged on the measured parameters. The surround studio has the best quality compared to the other studios. The reverberation times are flat, reflections appear only in the first 2 ms and are of very low level. The frequency response shows no interference pattern.

The LEDE has a flat reverberation time and low reflection levels but the earliest reflections from the console cause coloration of the sound that might be audible. Also, there are some later reflections that contribute to the sound build-up.

The three broadcasting studios have all reverberation times that decrease in frequency and can give a bassy impression. The reflections are contributing to the sound build-up also for later sound arrivals. The frequency responses all reveal interference patterns.

The broadcasting studios are characterized by big window surfaces. These windows are mostly facing towards the corridors and only provide insight and light intake. They are unnecessarily big in my opinion and deteriorate the studios quality.
However, during my visits at Kanalhuset I witnessed that the program presenters wore headphones in these studios and the small monitors on the tables were not used. This reduces the importance of the room's quality.
The broadcasting studios were chosen in the first place because the sound technicians experience that especially Studio 31 and Studio 32 do not allow a good working environment acoustically.

Furthermore, I want to name some future improvements that were discussed during my thesis presentation.
For the impulse response, it is more correct to study single octave bands. As the calculation model is by experience valid for higher octave bands only, the lower octave bands can distort the figure of the total impulse response.

Additionally, the results would be more correct if I had corrected the measured impulse response with a measurement of the sound pressure level 1 m on axis. In this way, I would have compensated the measurements from the loudspeakers frequency range. The monitors used in the LEDE and the surround studio show that they are not flat over the whole frequency range.

For the thesis, I performed the measurements first and ran my calculations afterwards. It could be beneficial for the outcome of the thesis to calculate the rooms first. In this way, the calculated results might give indications of problematic reflections that can be further investigated by measurements.

In the future, it might be better to focus on one room and put more time in developing a good measurement program in order to get better correspondence with calculation. It is hard to get hold of source data from producers that are accurate. In the future, the used sound source should be studied carefully in order to have correct and reliable input data for the calculation model.

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