# CONCERT HALL ACOUSTIC COMPUTER MODELLING: AMSTERDAM CONCERTGEBOUW

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*Abstract – This paper presents the comparison between acoustic measuring and simulation. It starts with a complete analysis of the acoustic parameters of the Amsterdam Concertgebouw and then a 3D model is made in order to simulate the acoustic conditions and compare with the RIR measured into the concert hall. The modelling process is detailed in this paper including the different stages that led to a similarity with the measured parameters.*

## 1. INTRODUCTION

Room acoustic computer modelling has been practised for almost 50 years up to date. Nowadays, it is almost impossible to think in any concert hall acoustic design and prediction without this modelling techniques.

In order to establish a comparison between the acoustical behaviour of concert halls, there are some objective parameters that describes the subjective listener's sensation in a concert hall.

The objective of the present work is to model a real concert hall with a commonly used software and obtain some acoustical parameters. Then, these values are compared with the parameters obtained through some impulse response measured into the room. Finally, the model is modified to achieve the most similar values from modelling to the measured ones.

## 2. ACOUSTIC COMPUTER MODELLING

In acoustics, a phenomenon could be described by particles or either by waves behavior. A wave model for sound propagation is characterised by creating very accurate results at single frequencies. The problem is that in acoustics, it is important to obtain results in octave bands. Also, the number of natural modes increases with the third power of the frequency, so the wave model is restricted to low frequencies and small rooms.

Otherwise, it is possible to describe the sound propagation as sound rays, similar to light ones. This is a geometrical model that achieve accurate results at mid and high frequencies in large and complex structures. Two of the classic geometrical methods are commonly known as Ray tracing and Image source method.

### 2.1. Ray Tracing Method

The Ray Tracing Method uses a source point that radiate many particles or rays with speed of sound to all directions in a closed space. Every surface has an absorption coefficient, so the particle loses his energy on every reflection and also with long travels due to air absorption.

The ray direction after any reflection obey the Snell's law that claims that the angle of incidence is equal to the angle of reflection (specular reflection).

In order to obtain a calculation result in some specific receiver point, an area or volume should be defined. Then the sound rays are caught travelling by this area. If the area of the wave front per ray is not larger than A/2 (meaning A the total area), it is almost a certainty that the ray will discover a surface with the area A after having travelled the time t. Then, according to the J. H. Rindel studies [1], the minimum number of rays could be calculated by the equation:

$$N \geq \frac{8\,\pi\,c^2}{A} t^2 \tag{1}$$

where c is the speed of sound in air.

Figure 1 shows a ray tracing method in a shoebox shaped room:

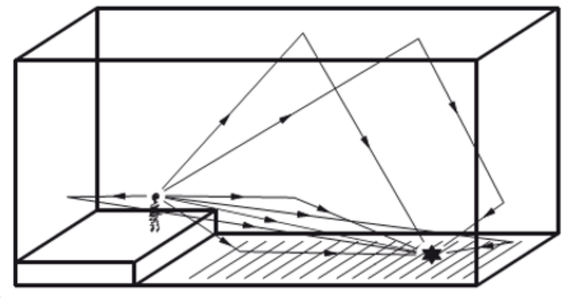

Figure 1. Example of Ray tracing method.

**2.2. Image Source Method**

The Image Source Method generates a specular reflection mirroring the source in the plane of the reflecting surface. This, is clearly shown in figure 2, where $A_1$ is the first order image source (mirror image of the source), $A_2$ is the second order image source (mirror image of the first order mirror image) and so on.

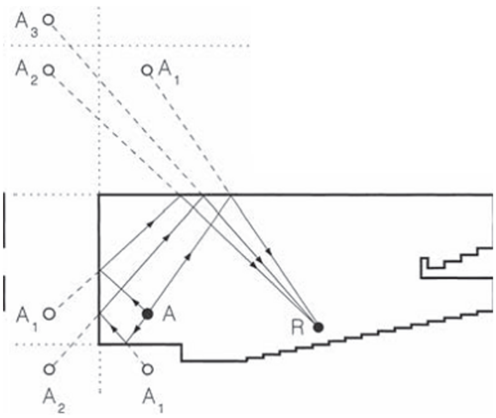


Figure 2. Example of Image Source Method.

This method is very useful for calculating early reflections in simple rectangular rooms. The problem is that the image source number grows exponentially with increasing the reflection order and then increasing the computational time.

Number of reflections at the receiver point, up to time *t,* could be obtained with the room volume *V* as shown in equation 2:

$$N_{refl} = \frac{4\pi c^3}{3V} t^3 \tag{2}$$

In fact, the number of reflections decreases with the volume and increases with time in the third power, according to equation 2.

## 3.ACOUSTIC PARAMETERS

Any listener, performer or conductor could describe the sound quality providing by a concert hall in a music passage. They use some subjective descriptor as reverberance, clarity, loudness, spaciousness, etcetera. Most of these are generally recognized as relevant descriptors of mayor aspects of the acoustics in rooms. The problem is that these descriptors can not be compared between multiple concert halls because they do not represent an objective value.

This situation has promoted standardization of measurement methods and many of the objective parameters are now described in an appendix to the International Organization for Standardization (ISO) standard [2].

The objective parameters used in this paper are described based on the acoustical theory provided by Glen Ballou [3], Leo L. Beranek [4], Thomas D. Rossing [5] and Michael Barron [6].

### 3.1. Reverberation time

One of the most important subjective parameters to describe the acoustic behaviour of a room is the reverberance. When a room creates too much reverberance, speech loses intelligibility because important details (consonants) are masked by louder speech sounds (vowels). In music, the reverberance can add an attractive fullness to the sound by bonding adjacent notes together and blending the sound from different instruments in an ensemble.

In the late 1890s, Wallace Clement Sabine described the objective parameter reverberation time as the time it takes for the sound level in the room to decrease by 60 dB after a continuous sound source has been shut off. He established a relationship between this parameter, the volume of the room $V$ and its total absorption (in sabins). This is given by the equation:

$$RT_{60} = 0{,}161 \frac{V}{S\alpha} \qquad (3)$$

where S is the total surface area in $m^2$ and $\alpha$ is the average absorption coefficient of room surfaces.

In practise, it is hard to reach 60 dB between signal and background noise, so people uses a smaller interval of the decay curve, for example, from -5 dB to -35 dB, below the start value. Then, a regression line of this decay curve defines the time that would take to this sound to decay 60 dB. This parameter called $T_{30}$ is shown in the following figure:

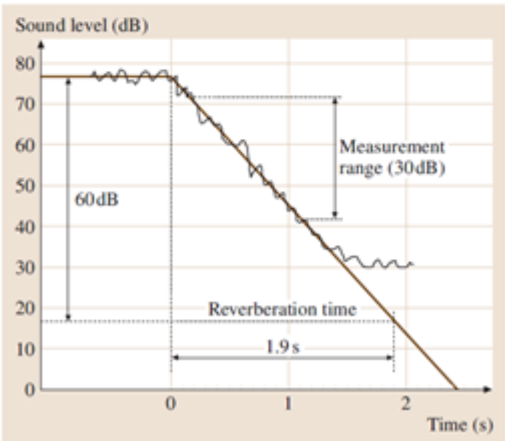


Figure 3. Regression line implementation to obtain the RT.

In the same way, another value could be obtained from -5 dB to -25 dB below the start value of the decay curve, meaning the $RT_{20}$ value.

### 3.2. Early Decay Time

Another parameter related with the reverberance perceived during running speech and music is the Early Decay Time (EDT). This alternative parameter also measures the time that takes for a sound to decay after it is cutted off, but evaluated from the initial period, the interval between 0 and -10 dB. Then this time is multiplied by a factor of 6 in order to establish a direct comparison between EDT and RT.

Usually the EDT indicates acoustical quality better than RT does because notes played by violinists in symphonic compositions follow each other very rapidly, therefore only the early part of the sound decay process remains audible between successive notes.

Both parameters EDT and RT are highly influenced by room diffusion. In a hypothetical highly diffusive space where the decay is completely linear, the two quantities would be identical. Also, if RT values in octave bands stay almost the same all along the hall, this is a diffusive room for all the frequencies.

### 3.3. Speech Transmission Index

In any room used for speech, such as lecture halls, theatres or classrooms, the influence of the acoustics on intelligibility is a major issue. For this reason, Houtgast and Steeneken [7] created a way to measure the speech intelligibility with an objective parameter called STI: Speech Transmission Index.

This measure is based on the idea that speech can be regarded as an amplitude-modulated signal in which the degree of modulation carries the speech information. The modulation transfer is tested by emitting noise in seven octave bands, each modulated with 14 different modulation frequencies and then calculating the ratio between the original and the received degree of modulation, the modulation reduction factor. This reduction factor results in a number between 0 and 1 corresponding to very poor and excellent conditions, respectively.

### 3.4. Alcons

Another objective parameter to measure speech intelligibility is the Percentage of Articulation Loss of Consonants (%Alcons) that describes how many percent of the consonants are unintelligible.

It is based on statistical parameters as the RT and Volume of the room and directivity of the source and does not take into account, for example, the reflections. Then the speech intelligibility can be judged as good if the Alcons value is below 10%, reasonable if between 10 and 15% and bad above 15%.

### 3.5. Echo parameters

Echo is a reflection of sound that arrives at the listener with a delay after the direct sound. The cause of echo-disturbances during presentation of music and speech in rooms has been investigated by Dietsch and Kraak [8]. They proposed a way to quantify the echo criteria EK for music and speech.

First of all, it is needed to present the center time $t_s$ defined by Kurer as the ratio between the summed-up products of the energy components of the arriving sound reflections and the corresponding delay times and the total energy component as shown in equation 4.

$$t_s(\tau) = \frac{\int_0^\tau |p(t)|^n(t)dt}{\int_0^\tau |p(t)|^n dt} \tag{4}$$

where the incoming sound reflection n = 0.67 with speech and n = 1 with music.

Comparing it with the difference quotient:

$$EK(\tau) = \frac{\Delta t_s(\tau)}{\Delta t_E} \tag{5}$$

Then, we can discern echo distortions for music or speech when applying values of 14 ms for music and 9 ms for speech.

### 3.6. Lateral Fraction

In the late 1960s through listening experience and research, Harold Marshall discovered that early reflections arriving from lateral directions created a desirable sense of spaciousness [9].

A few years later, Marshall and Barron derived the “early lateral energy fraction” (LF) as a linear measure of spatial impression [10]. They found that the degree of spatial impression was maximised when the sound arrived side on to the listener. LF is generally measured from impulse responses obtained using a “figure of 8” and an omnidirectional microphones to measure the lateral and total energy respectively. This value could be calculated by equation 6:

$$LF = \frac{\int_{0.005}^{0.080} {P_L}^2(t)dt}{\int_0^{0.080} P^2(t)dt} \tag{6}$$

where $P_L(t)$ is the impulse response measured with the figure of 8 microphone and the P(t) is the signal measured with the omnidirectional microphone.

### 3.7. Sound Pressure Level

The perceived loudness of a sound event is related to its acoustical level. Levels are electrical or acoustical pressures or powers expressed in decibels. Sound pressure level is the pressure deviation from the ambient atmospheric pressure caused by a sound wave in some point and it is defined by the equation:

$$SPL = 20log_{10}\frac{p}{p_{ref}} \tag{7}$$

where $p_{ref}$ is the ambient atmospheric pressure with a value of 20 $\mu Pa$.

### 3.8. D/R ratio

D/R ratio is defined as the quotient between direct sound energy from the source and reverberant sound energy measured in some point of the room. Both energy values are obtained from an impulse response as it is present in the following equation:

$$D/R = \frac{\int_0^T h^2(t)dt}{\int_T^\infty h^2(t)dt} \tag{8}$$

where h(t) is the impulse response measured in some point of the room and T is chosen such that it separates the direct sound from all reflections in the impulse response.

Time T used in calculation on this paper is 20 ms. This value selection is based on Antoni Carrion Isbert recommendation of ITDG for halls, where ITDG corresponds to the delay gap between direct sound and first reflection, Initial Time Delay Gap [11].

## 4.CONCERT HALL SELECTION: AMSTERDAM CONCERTGEBOUW

The concert hall selected to model and simulate in the acoustical modelling software EASE was the Royal Concertgebouw situated in Amsterdam, Netherlands. The dimensions, materials and any other characteristic were obtained from Beranek's book [4]. He also provides a table with objective parameters for any of the 100 concert halls and opera houses presented on the book.

Measured room impulse responses were obtained from Samplicity site [12], which provides RIR to use in Altiverb plugin (audio reverb plugin with convolution processing). This compressed file had inside a folder with Altiverb's file to obtain the IR with an unknown extension, meaning we could not obtain directly the .WAV files in order to process the RIR. Analyzing the situation, an alternative method was decided in order to get effectively the audio: in Matlab, an almost perfect impulse response was synthesized with an amplitude of 0.7 (referring to 1 as a maximum) in 48 KHz of sample rate, writing a .WAV file of 1 second of duration. This was imported in a Pro Tools 10 HD session with the Audio Ease Altiverb Plugin inserted in a stereo track. The synthesized IR was duplicated into a stereo file and processed in Pro Tools in order to obtain .WAV files that represent the measured RIR in different positions. As a result of this process, the RIR were obtained for every position recorded.

Considered one of the three best concert halls with the Vienna's Grosser Musikvereinssaal and the Boston Symphony Hall, it opened in 1888 and it is still open nowadays. The architect of the building was Adolf Leonard Van Gendt, who was inspired by the Gewandhaus in Leipzig.

Concertgebouw has a shoe-box shape and 2037 seats. It is used for all types of music, with emphasis on orchestra. Today some nine hundred concerts and other events per year take place in the Concertgebouw for a public of over 700.000, making it one of the most visited concert halls in the world.

The following table shows the technical data provided by Beranek [4]:

Table 1. Concertgebouw Technical data.

| Dimension | Value |
|---|---|
| **Volume** | 18.780 $m^3$ |
| **Number of seats** | 2037 |
| **Average room height** | 17,1 m |
| **Average room width** | 27,7 m |
| **Average room length** | 26,2 m |
| **Acoustical absorption area** | 1285 $m^2$ |
| **Area of the floor space where the seats are located** | 843 $m^2$ |
| **Acoustical Audience area** | 1125 $m^2$ |
| **Distance from the front of the stage to the most remote listener** | 25,6 m |
| **Stage area** | 160 $m^2$ |

Figures 4 and 5 show the plans provided by Beranek, corresponding to the floor plan with the two levels of seats and the cross-section plan with the scale, respectively:

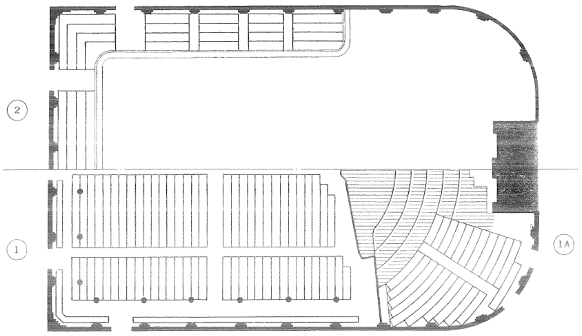


Figure 4. Floor plan of the concert hall.

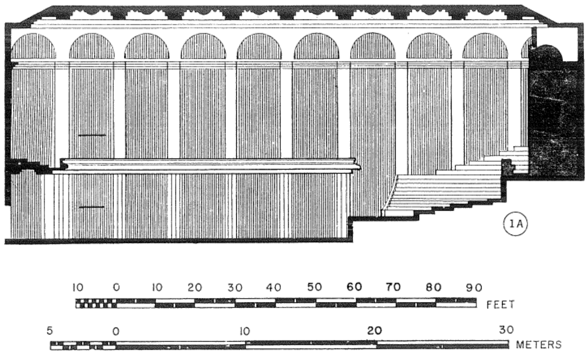


Figure 5. Cross-section of the concert hall.

The hall is also used for social events, amplified music and balls and offers guided visits through the installations. Figures 6 to 8 show some real pictures of the room in different applications.

Figure 6: Rock concert at Amsterdam Concertgebouw.

Figure 7: Waltz Ball at Amsterdam Concertgebouw.

Figure 8: Symphonic orchestra playing at Amsterdam Concertgebouw fully occupied.

### 4.1. Concert hall 3D model

The entire 3D model was based on information found in Beranek's book, the Concertgebouw's webpage images and pictures provided by the people who measured the impulse response. It was designed in Sketchup 2015, exporting the versions in Sketchup 7.0 format in order to be compatible with the EASE modelling software. The complete simulation process required 9 models to be performed in order to have the closest parameters; the most relevant of them are described.

Model ‘v1’ implemented a basic shape in order to check the calculated volume in both softwares and to make sure this drawing mode was the right one, closing the figure and leaving no unnecessary free line into it, which generates errors in EASE. No stage was implemented, this was used to check the first stage of the relationship between the 3D model and the imported in the modelling software.

In ‘v2’ the stage with steps was implemented and some audience areas were drawn in order to check the impact of switching between absorption coefficients for this group. It is important to take in mind that the audience area is almost always the most important absorptive surface into any concert hall, so it would have a big impact on the RT simulated.

Versions 3 and 3.1 had balconies implemented with different drawing styles in order to check the best compatible with EASE. Later, version 4 added audience areas in the whole room, including the stage ones.

‘v5’ included the main entrance door to the room from the exterior. Taking in mind there are at least 18 doors, they represented a big area in the room. Later, ‘v6’ added the big organ which represents an essential part of this famous concert hall.

Every audience area was elevated 1.2 m (average head position of seated audience) and treated as a rectangular area. It was chosen for an easier simulation in EASE and also to represent this areas as a measurement by the Kath & Kull [13] method for measuring concert hall seats.

Also, some things from the original concert hall had to be modified in order to work properly on EASE. The rounded surfaces had to be turn into squared ones and the ornaments were not copied. Instead of that, scattering coefficients supplied the acoustic effect provided by the columns and arcs.

The presented rendered images are in similar positions to the real pictures in order to have a comparison from the same perspective. In addition, a plan is shown and a lateral cut also, both with additional lightning artefacts to add realism.

Figure 9 shows the real picture and then figure 10 shows the rendered one.

Figure 9: View from audience in stage. Real photo.

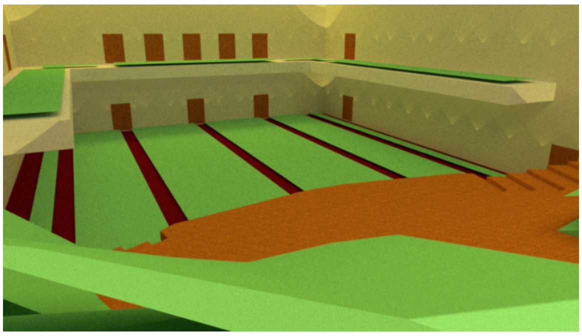

Figure 10: Rendered view from audience in stage.

The same comparison is shown in Figures 11 and 12.

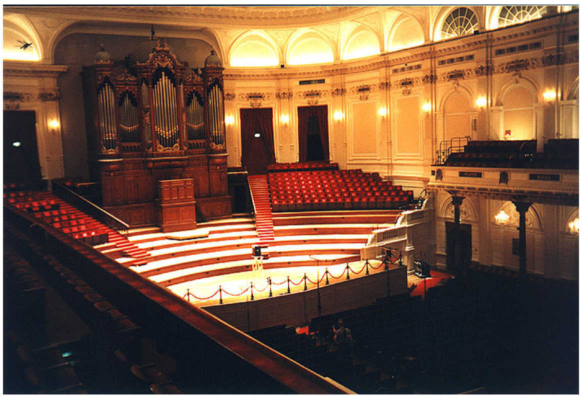

Figure 11: View from balcony. Real photo.

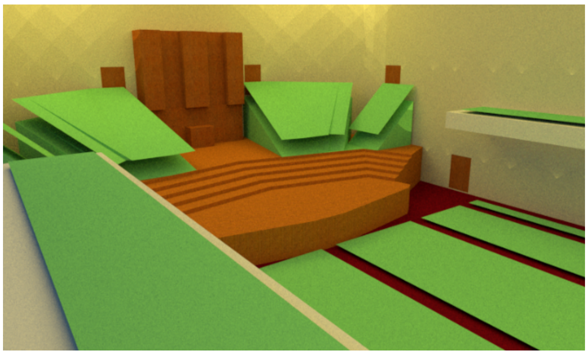

Figure 12: Rendered view from balcony

The 3D model plan is shown in Figure 13 with a cross section in Figure 14.

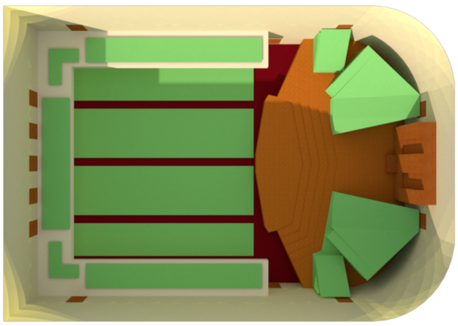

Figure 13: 3D model in top view.

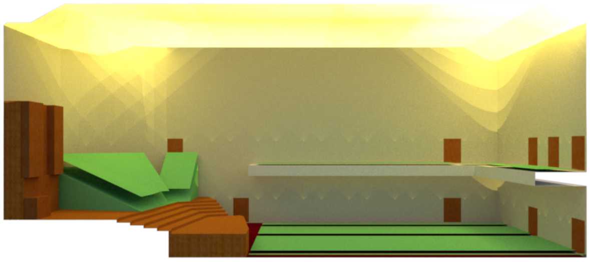

Figure 14: Cross-section of 3D model.

**4.2. Computer simulation implementation: Results and comparison**

An acoustic simulation of the Concertgebouw Hall was performed in EASE 4.3 through raytracing and room mapping. Impulse responses generated and measured were analyzed with the software EASERA 1.0.60.

A first 3D Model without balconies was created in order to have an initial estimate of room parameters. The surfaces, materials and absorption coefficients taken from [14] are shown in Annex, Table 2.

CAD model is shown in Figure 1 with listener seats and loudspeaker position. Loudspeaker was placed on the front and center of the stage which corresponds to the position where source was placed during IR measurements. 19 listener seats were placed along the concert hall: 4 at balconies, 6 on floor audience area which correspond to the positions where microphones were placed during IR measurements (Positions 2,3,6,7,10 and 11), and 6 more to cover the floor audience area. Also 2 listener seats were placed on the audience area over the stage.

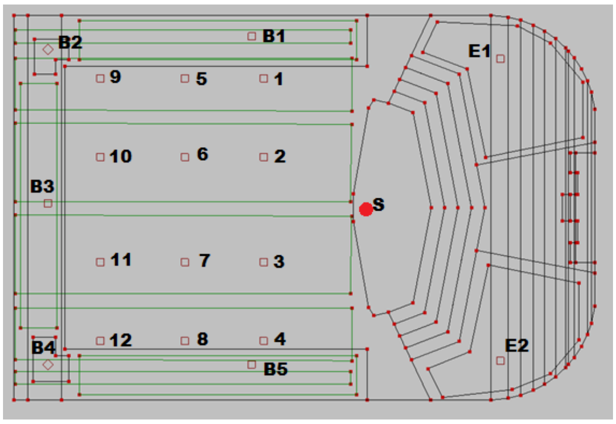


Figure 15. Floor Plan View of CAD model with listener seats and loudspeaker position

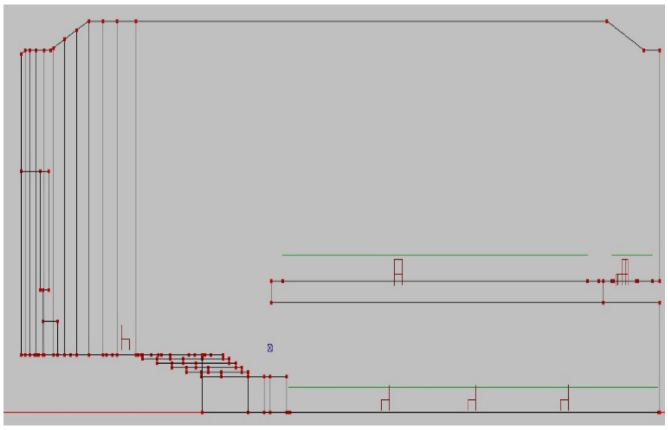

Figure 16. Side view of CAD model with listener seats and loudspeaker position

Table 2. Listener Seat and Loudspeaker Absolute Coordinates positions.

| Absolute Coordinates (m) | | | |
|---|---|---|---|
| | X | Y | Z |
| S | 37 | 24,5 | 3 |
| 1 | 29 | 34,5 | 1,2 |
| 2 | 29 | 28,5 | 1,2 |
| 3 | 29 | 20,5 | 1,2 |
| 4 | 29 | 14,5 | 1,2 |
| 5 | 23 | 34,5 | 1,2 |
| 6 | 23 | 28,5 | 1,2 |
| 7 | 23 | 20,5 | 1,2 |
| 8 | 23 | 14,5 | 1,2 |
| 9 | 16,6 | 34,5 | 1,2 |
| 10 | 16,6 | 28,5 | 1,2 |
| 11 | 16,6 | 20,5 | 1,2 |
| 12 | 16,6 | 14,5 | 1,2 |
| B1 | 28,1 | 37,7 | 7 |
| B2 | 12,6 | 36,7 | 7 |
| B3 | 12,6 | 25 | 7 |
| B4 | 12,6 | 12,7 | 7 |
| B5 | 28,1 | 12,7 | 7 |
| E1 | 47 | 36 | 4 |
| E2 | 47 | 13 | 4 |

Comparisons and corrections were done using a fixed listener seat (Position 2) and its corresponding measured impulse response. EDT and T20 values were evaluated and optimized at a first instance. First simulation results are shown in Annex, figures 17 and 18.

It can be seen that when balconies are added to the model, the large absorbing surface lowers early decay time and reverberation time. Anyway, EDT curve fits measurements but simulated T20 is significantly lower. Seats absorption coefficients are the most sensible variables as large differences result from different seating spaces, amount of upholstery and edge effect. This indicates that absorption coefficients used are higher than real ones so in the next simulation coefficients were lowered.

Simulated T20 gets closer to real one but EDT is higher so in the next simulation scattering coefficients are added to lateral walls and ceiling. Scattering coefficient values are calculated taking into account the dimensions of the ornamentations used at each surface of Concertgebouw Hall. As ornamentations in lateral walls are detailed and with small dimensions, scattering effects occur at high frequencies. In the other hand, there are deep "window" recesses at the ceiling so scattering effects occur at lower frequencies for this surface (see Figures 20 and 21). When scattering effects are considered, T20 and EDT curves get closer as seen in Figures 19 and 20 from Annex. Values of diffuser's scattering coefficients from Annex C from [14] were taken as a reference of scattering usual values.

Figure 20. Ceiling View of Concertgebouw Hall.


Figure 21. Lateral Wall View

Simulations were performed with a cutoff time of 1 second, a cutoff order of 25 and 2500000 rays per speaker resulting in a 99.5% of impact chance. The impulse response was postprocessed adding a predicted impacts tail of 3 seconds. The total impulse response length is 4 seconds, enough to decay 60 dB for all frequency bands. The cutoff order was chosen taking into account the mean free path time which is 0,04 seconds for this model, so in this case, reflections of order 25 would take 1 second as mean time which is the cutoff time.

The raytracing process took in average 5 hours and 20 minutes. Shorter simulations were performed in between longer ones in order to adjust and check the model. These shorter simulations were performed with a cutoff order of 15 and a cutoff time 750 ms, 700000 rays per loudspeaker and a resulting impact chance of 91%. These shorter simulations took in average 1 hour.

The computer used for simulations has a I7-4770K processor with 3.5 GHz clock speed and 16 GB of RAM.

Details of results of T20 and EDT for each simulation are shown in Annex, tables 3 and 4.

According to results shown, the scattering optimized model was chosen for a longer simulation and detailed analysis. In Table 5 and 6, from Annex, final absorption and scattering coefficients for each surface are specified.

A long simulation with cutoff order of 40 and cutoff time of 1.5 seconds was performed. For a further analysis of the raytracing method, the impacts file was copied at 20%, 40%, 60% and 80% of progress in order to analyze the dependence of the number of rays with the estimation of T20 and EDT values. The results shown in Figures 22 and 23, in Annex, highlight the problem that as the number of rays increase, the energy at low frequencies grows. This is caused because raytracing method ignores phase and destructive interference so at low frequencies all rays sum their energy. By this analysis it was found that a shorter simulation gave better results than a long one, so this was discarded.

Results of simulation are shown in Table 7 and compared to measured ones shown in Table 8. Differences are shown in Table 9.

It can be seen from Table 9 that T20 differences between simulation and measurements were lower than a 10% (maximum deviation at 4 kHz). Global indexs like STI and ALCONS also were well approximated by simulation with differences lower than 3% of measured values.

Higher differences are seen in EDT values particularly at low frequencies where the raytracing method is weak. Highest difference is observed at lower frequency band and lowest difference at highest frequency.

Differences in echo speech and music are the greatest, although simulation results seem more coherent as higher level reflections occur at shorter times (between 20 and 80 ms). In measurements these strong reflections occur between 40 and 140 ms. Echo Speech and Music results are very dependent on the estimation of arrival time which introduces uncertainty, and measurements are noisy. Also, for example, by inspecting Echo Speech of Figure 24 in Annex, it can be seen that there are two peaks of almost the same level, and this difference of level could be caused by noise, so the parameter is very sensible to real conditions measurement variables.

In order to determine the time of arrival of the first reflections, an echogram was computed using a median highpass filter. An example of echogram is shown in Annex (figure 25). All impulse responses had an ITDG between 20 and 30 ms, so 20 ms were used to compute D/R.

There is a difference of 3.6 dB between D/R of measurement and simulation. This can be caused by noise in the measurement or by an incorrect estimation of scattering and absorption coefficients.

Finally, SPL information was not available in IR measurements as their amplitude was normalized, but a room mapping of SPL was computed over the audience area in the simulated model as seen in Figures 26 and 27 from Annex. Sound pressure level seems homogeneous along the hall. In higher frequency bands like 8kHz as shown in Figure 14. SPL is no more homogeneous and it vanishes as distance from source grows.

## 5. Conclusions

Raytracing as a room acoustics simulation method can offer a good estimate of main acoustic parameters at high frequencies but at low ones the method lacks precision as wave phase is not taken into account. Also, absorption and scattering coefficients need to be precisely estimated in order to have a coherent result. In large surfaces, as for example the seating area, a small difference in coefficients can result in a big difference of predicted acoustic parameters. Also, if the inverse process of determining the materials absorption coefficients from measured IRs and an optimization of simulations is done, this problem deals with a large amount of variables and many possible solutions. Simulated impulse responses could show fitted acoustic parameters but coefficients not be the real ones. Also, adding a tail could allow shorter simulations, but deteriorate impulse response quality. Coherent acoustic parameters could be achieved but resulting auralizations be of poor quality.

Concluding, raytracing can give a good initial estimate of high frequency parameters in the acoustic design stage of a room if measured coefficients are supplied, but for a low frequency analysis, other techniques like FEM or BEM should be performed.

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# Annex

Table 2. Initial materials absorption coefficients

| | | | Absorption Coefficients | | | | | |
|---|---|---|---|---|---|---|---|---|
| Surface | Area (m2) | Material | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| Ceilings | 1655,44 | Lime Cement Plaster | 0,02 | 0,02 | 0,03 | 0,04 | 0,05 | 0,05 |
| Floor Seating | 557,28 | Upholstered Seating | 0,45 | 0,6 | 0,73 | 0,8 | 0,75 | 0,64 |
| Stage Seating | 148,53 | Upholstered Seating | 0,45 | 0,6 | 0,73 | 0,8 | 0,75 | 0,64 |
| Balcony Seating | 194,24 | Upholstered Seating | 0,45 | 0,6 | 0,73 | 0,8 | 0,75 | 0,64 |
| Lateral Walls | 1572,86 | Plaster on Brick | 0,013 | 0,015 | 0,02 | 0,03 | 0,04 | 0,05 |
| Organ | 135,71 | Wood platform large airspace below | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,1 |
| Stage Floor | 350,36 | Wood platform large airspace below | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,1 |
| Balconies | 75,3 | Lime Cement Plaster | 0,02 | 0,02 | 0,03 | 0,04 | 0,05 | 0,05 |
| Carpets | 364,27 | Carpet on Concrete | 0,02 | 0,06 | 0,14 | 0,37 | 0,6 | 0,65 |

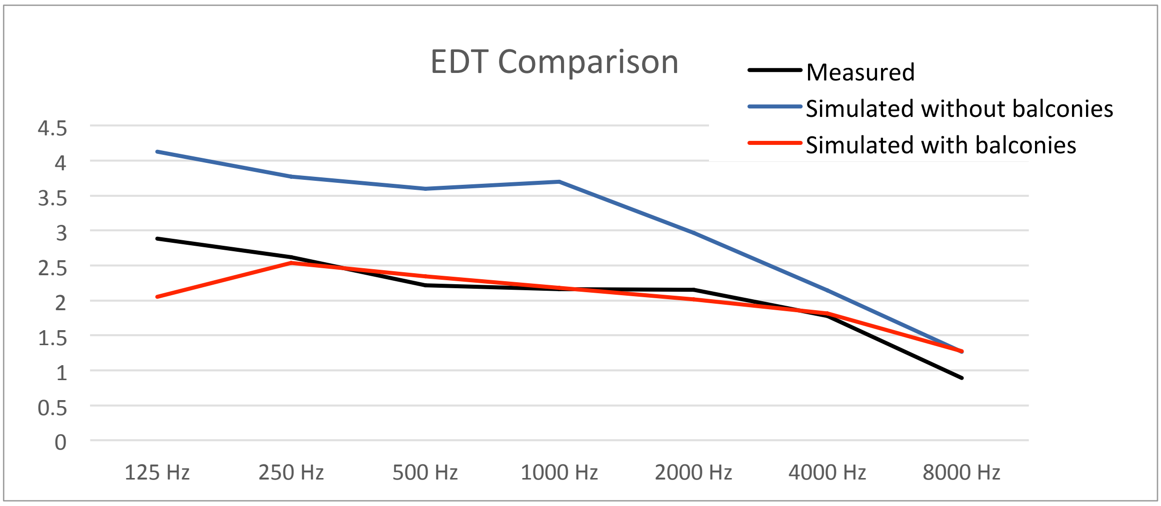


Figure 17. Early Decay Time comparison between measured and simulated results.

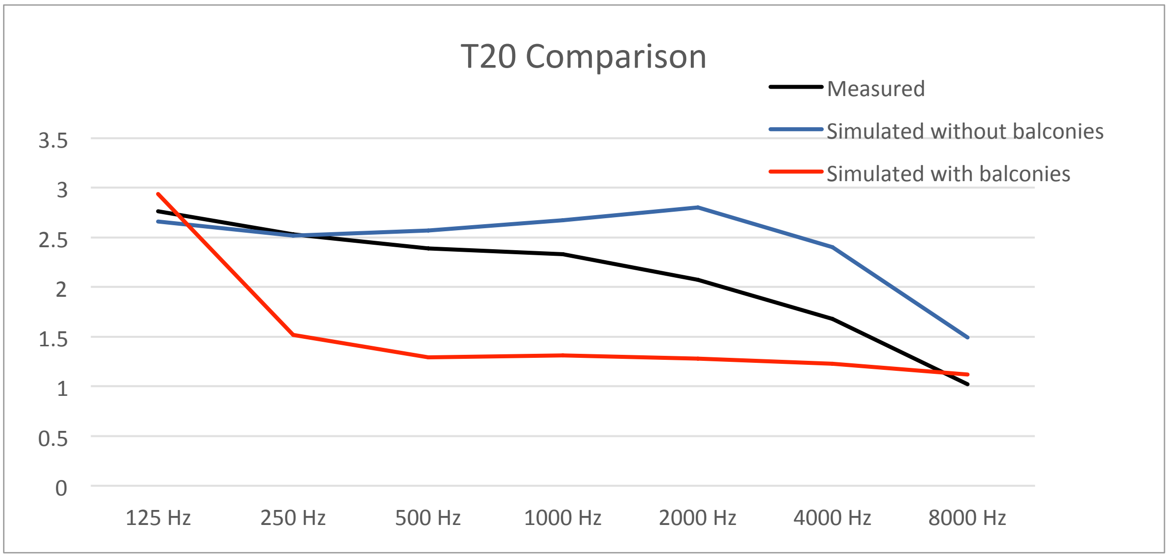

Figure 18. Reverberation Time comparison between measured and simulated results.

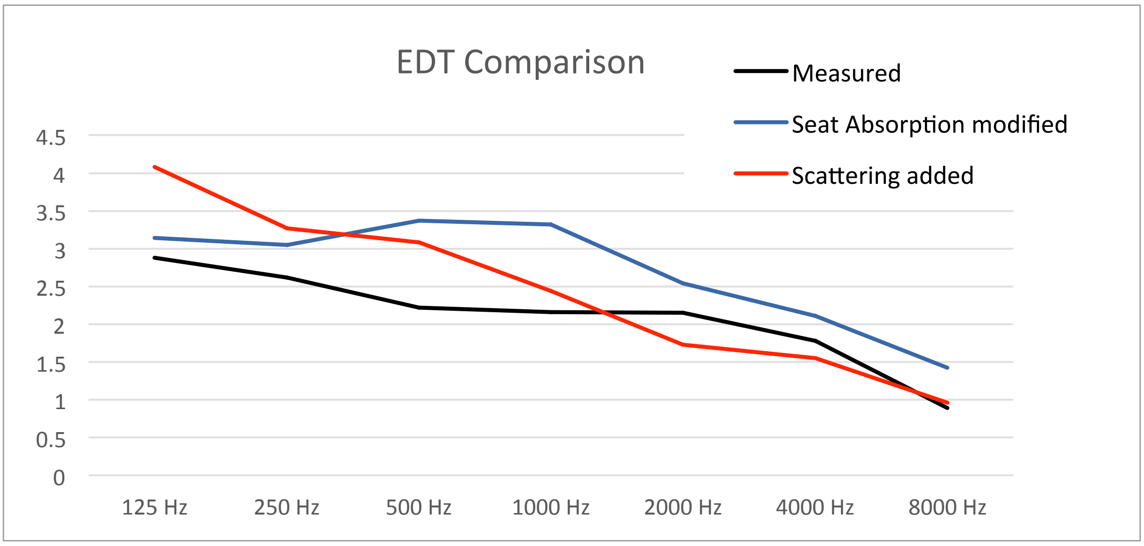


Figure 19. Early Decay Time comparison between measured and simulated with seat absorption modified and scattering added

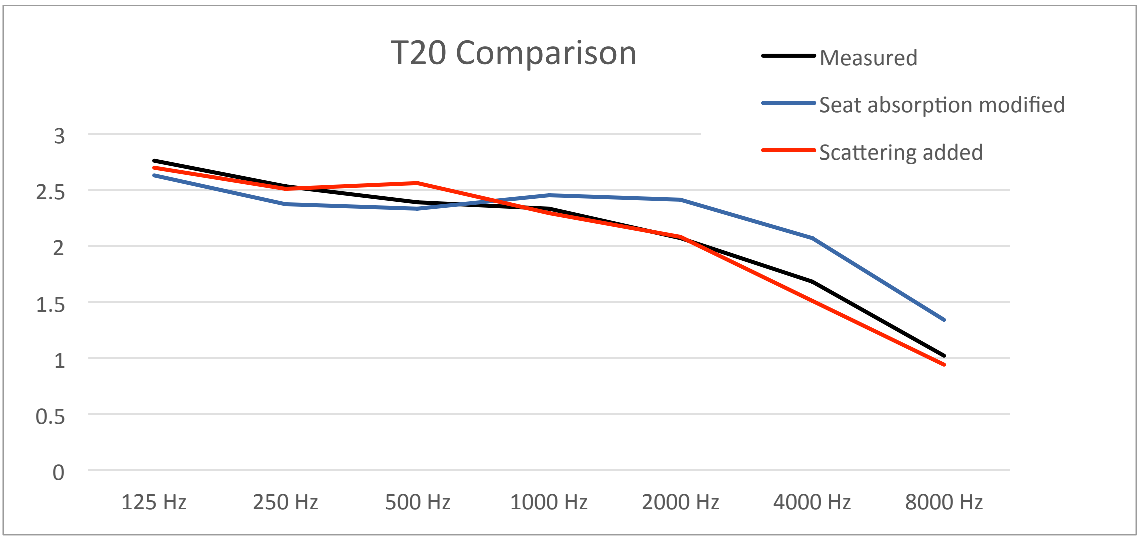


Figure 20. Reverberation Time comparison between measured and simulated with seat absorption modified and scattering added.

Table 3. T20 results of different short simulations.



| | T20 (s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | 250Hz-2kHz | 500Hz-4kHz |
| Measured | 2,76 | 2,53 | 2,39 | 2,33 | 2,07 | 1,68 | 1,02 | 2,11 | 2,11 |
| No Balconies | 2,66 | 2,52 | 2,57 | 2,67 | 2,8 | 2,4 | 1,49 | 2,64 | 2,61 |
| Balconies | 2,94 | 1,52 | 1,29 | 1,31 | 1,28 | 1,23 | 1,12 | 1,35 | 1,28 |
| Absorption optimized | 2,63 | 2,37 | 2,33 | 2,45 | 2,41 | 2,07 | 1,34 | 2,39 | 2,32 |
| Scattering optimized | 2,7 | 2,51 | 2,56 | 2,29 | 2,08 | 1,51 | 0,94 | 2,36 | 2,11 |

Table 4. EDT results of different short simulations.

| | EDT (s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz | 250Hz-2kHz | 500Hz-4kHz |
| Measured | 2,88 | 2,62 | 2,22 | 2,16 | 2,15 | 1,78 | 0,89 | 2,15 | 1,67 |
| No Balconies | 4,13 | 3,77 | 3,6 | 3,7 | 2,97 | 2,14 | 1,26 | 3,51 | 3,11 |
| Balconies | 2,05 | 2,54 | 2,34 | 2,18 | 2,01 | 1,81 | 1,27 | 2,27 | 2,08 |
| Absorption optimized | 3,14 | 3,05 | 3,37 | 3,32 | 2,54 | 2,11 | 1,42 | 3,07 | 2,83 |
| Scattering optimized | 4,08 | 3,27 | 3,08 | 2,44 | 1,73 | 1,55 | 0,96 | 2,63 | 2,2 |

Table 5. Final absorption coefficients of materials.

| | | | Absorption Coefficients | | | | | |
|---|---|---|---|---|---|---|---|---|
| Surface | Area (m2) | Material | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| Ceilings | 1655,44 | Lime Cement Plaster | 0,02 | 0,02 | 0,03 | 0,04 | 0,05 | 0,05 |
| Floor Seating | 557,28 | Upholstered Seating | 0,26 | 0,43 | 0,62 | 0,85 | 0,85 | 0,82 |
| Stage Seating | 148,53 | Upholstered Seating | 0,26 | 0,43 | 0,62 | 0,85 | 0,85 | 0,82 |
| Balcony Seating | 194,24 | Upholstered Seating | 0,26 | 0,43 | 0,62 | 0,85 | 0,85 | 0,82 |
| Lateral Walls | 1572,86 | Plaster on Brick | 0,04 | 0,05 | 0,05 | 0,06 | 0,07 | 0,07 |
| Organ | 135,71 | Wood platform large airspace below | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,1 |
| Stage Floor | 350,36 | Wood platform large airspace below | 0,4 | 0,3 | 0,2 | 0,17 | 0,15 | 0,1 |
| Balconies | 75,3 | Lime Cement Plaster | 0,02 | 0,02 | 0,03 | 0,04 | 0,05 | 0,05 |
| Carpets | 364,27 | Carpet on Concrete | 0,02 | 0,06 | 0,14 | 0,37 | 0,6 | 0,65 |

Table 6. Final scattering coefficients of materials.

| | | | Scattering Coefficients | | | | | |
|---|---|---|---|---|---|---|---|---|
| Surface | Area (m2) | Material | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| Ceilings | 1655,44 | Lime Cement Plaster | 0,03 | 0,05 | 0,08 | 0,11 | 0,16 | 0,16 |
| Floor Seating | 557,28 | Upholstered Seating | 0 | 0 | 0 | 0 | 0 | 0 |
| Stage Seating | 148,53 | Upholstered Seating | 0 | 0 | 0 | 0 | 0 | 0 |
| Balcony Seating | 194,24 | Upholstered Seating | 0 | 0 | 0 | 0 | 0 | 0 |
| Lateral Walls | 1572,86 | Plaster on Brick | 0,02 | 0,03 | 0,06 | 0,08 | 0,14 | 0,2 |
| Organ | 135,71 | Wood platform large airspace below | 0,01 | 0,01 | 0,02 | 0,03 | 0,05 | 0,06 |
| Stage Floor | 350,36 | Wood platform large airspace below | 0 | 0 | 0 | 0 | 0 | 0 |
| Balconies | 75,3 | Lime Cement Plaster | 0,03 | 0,05 | 0,08 | 0,11 | 0,16 | 0,16 |
| Carpets | 364,27 | Carpet on Concrete | 0 | 0 | 0 | 0 | 0 | 0 |

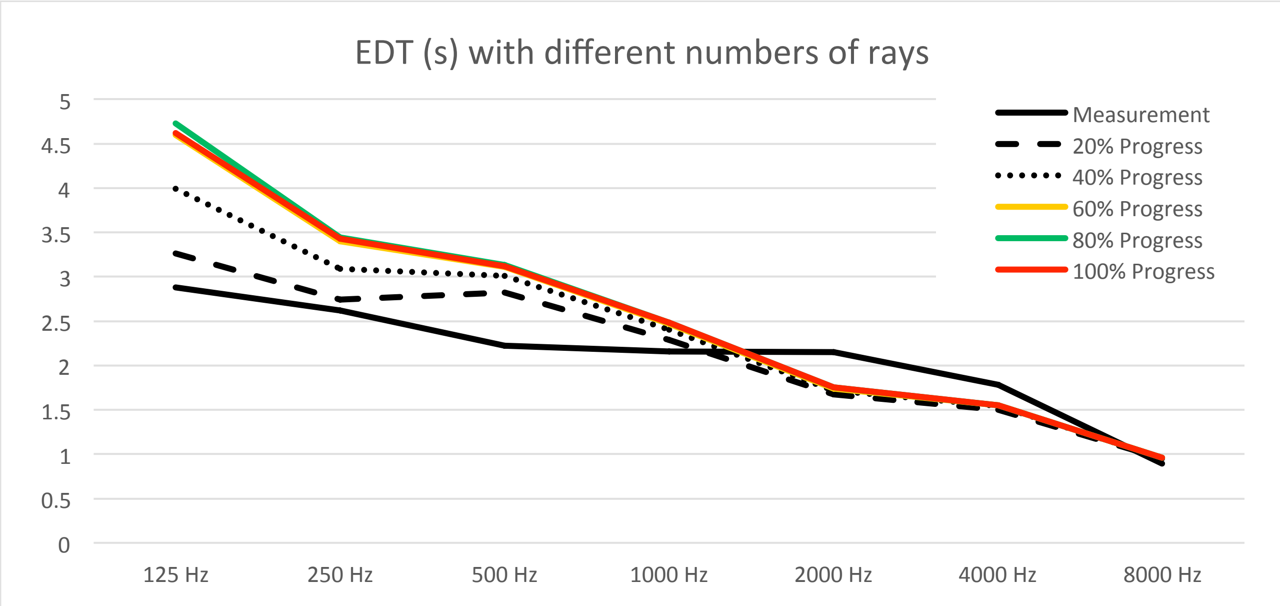


Figure 22. Early Decay Time comparison between measured and different number of rays.

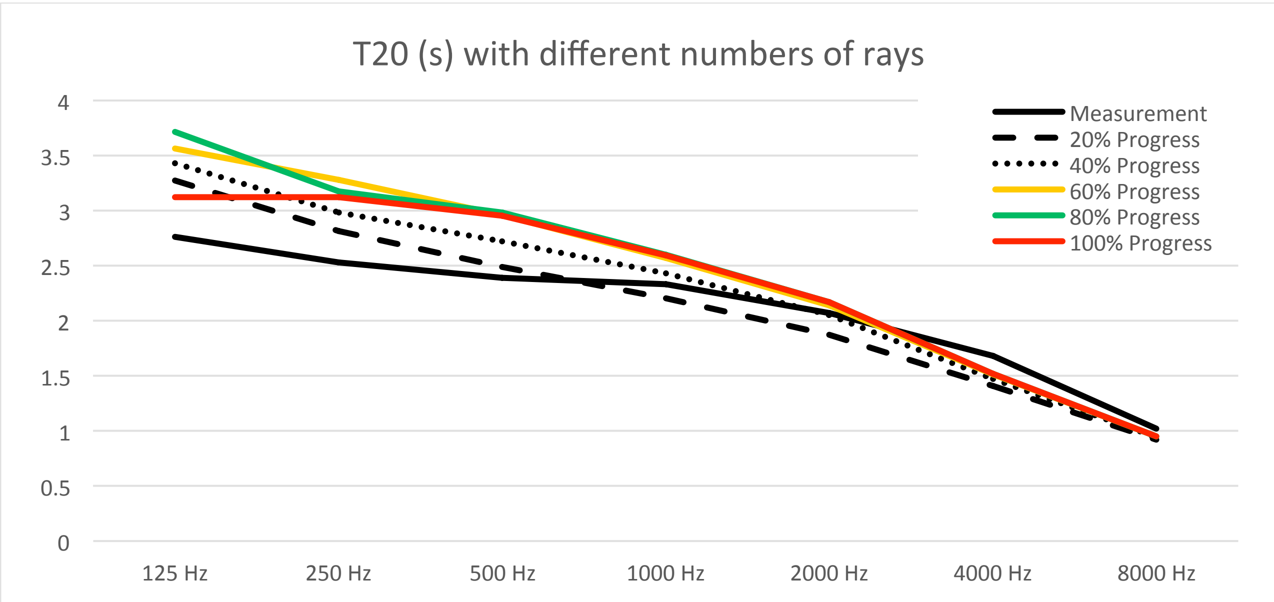


Figure 23. Reverberation Time comparison between measured and different number of rays.

Table 7. Results of simulation at Position 2.

| Simulation | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz |
| T20 | 2,66 | 2,52 | 2,56 | 2,29 | 2,08 | 1,51 | 0,94 |
| EDT | 4,06 | 3,27 | 3,08 | 2,44 | 1,73 | 1,55 | 0,96 |
| Echo Music (times) | 0,02 | 0,07 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 |
| Echo Music (max) | 1,03 | 1,02 | 1,04 | 1,38 | 1,41 | 1,39 | 1,29 |
| Echo Speech (times) | 0,02 | 0,06 | 0,06 | 0,06 | 0,06 | 0,05 | 0,08 |
| Echo Speech (max) | 1,08 | 1,24 | 1,04 | 1,84 | 1,84 | 1,79 | 1,69 |
| | | | | | | | |
| STI | 0,503 | | | | | | |
| ALCONS (%) | 11,19 | | | | | | |
| D/R (dB) | -9,40 | | | | | | |

Table 8. Results of measurement at Position 2.

| Measurement | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz |
| T20 | 2,76 | 2,53 | 2,39 | 2,33 | 2,07 | 1,68 | 1,02 |
| EDT | 2,88 | 2,62 | 2,22 | 2,16 | 2,15 | 1,78 | 0,89 |
| Echo Music (times) | 0,14 | 0,10 | 0,13 | 0,05 | 0,05 | 0,06 | 0,04 |
| Echo Music (max) | 0,72 | 0,70 | 0,72 | 0,67 | 0,63 | 0,66 | 0,70 |
| Echo Speech (times) | 0,13 | 0,10 | 0,13 | 0,05 | 0,05 | 0,07 | 0,04 |
| Echo Speech (max) | 0,70 | 0,74 | 0,70 | 0,70 | 0,64 | 0,65 | 0,65 |
| | | | | | | | |
| STI | 0,507 | | | | | | |
| ALCONS (%) | 10,93 | | | | | | |
| D/R (dB) | -5,80 | | | | | | |

Table 9. Differences between simulation and measurements.

| Differences | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz | 8000 Hz |
| T20 | 0,10 | 0,01 | 0,17 | 0,04 | 0,01 | 0,17 | 0,08 |
| EDT | 1,18 | 0,65 | 0,86 | 0,28 | 0,42 | 0,23 | 0,07 |
| Echo Music (times) | 0,12 | 0,03 | 0,07 | 0,01 | 0,01 | 0,00 | 0,02 |
| Echo Music (max) | 0,31 | 0,32 | 0,32 | 0,71 | 0,78 | 0,73 | 0,59 |
| Echo Speech (times) | 0,11 | 0,04 | 0,07 | 0,01 | 0,01 | 0,02 | 0,04 |
| Echo Speech (max) | 0,38 | 0,50 | 0,34 | 1,14 | 1,20 | 1,14 | 1,04 |
| | | | | | | | |
| STI | 0,004 | | | | | | |
| ALCONS (%) | 0,26 | | | | | | |
| D/R (dB) | 3,60 | | | | | | |

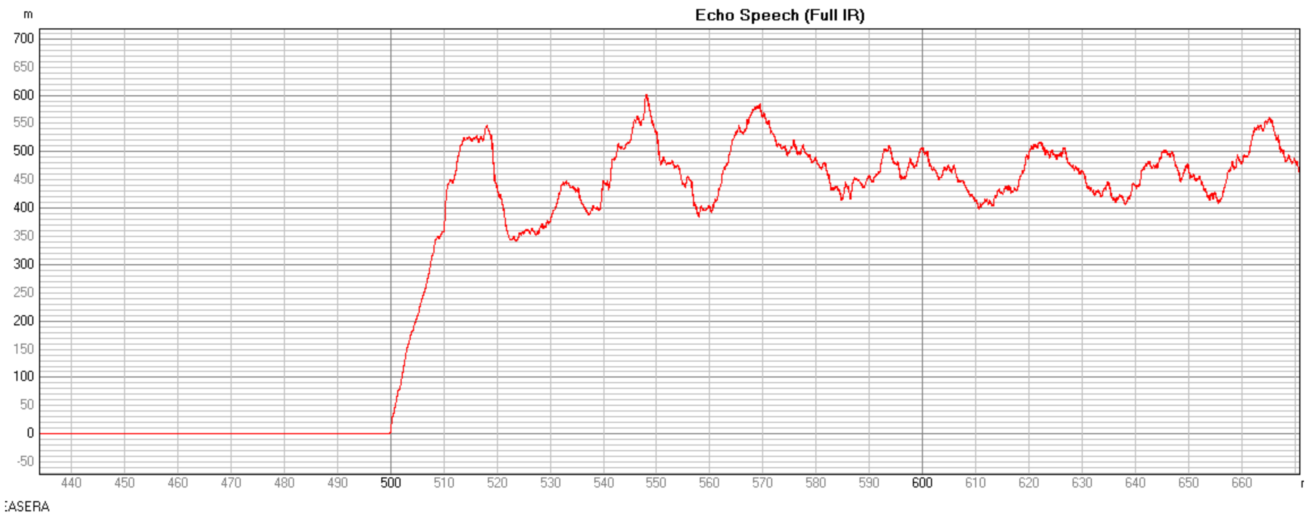


Figure 24. Echo Speech in time obtained from Easera.

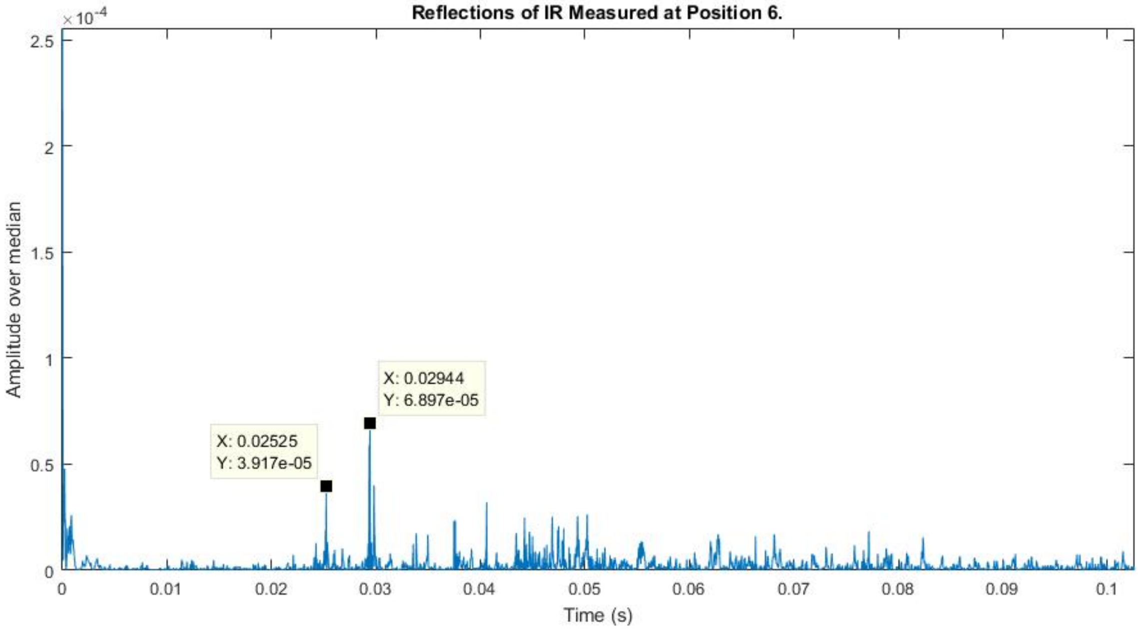


Figure 25. Example of echogram obtained from Matlab using a median highpass filter.

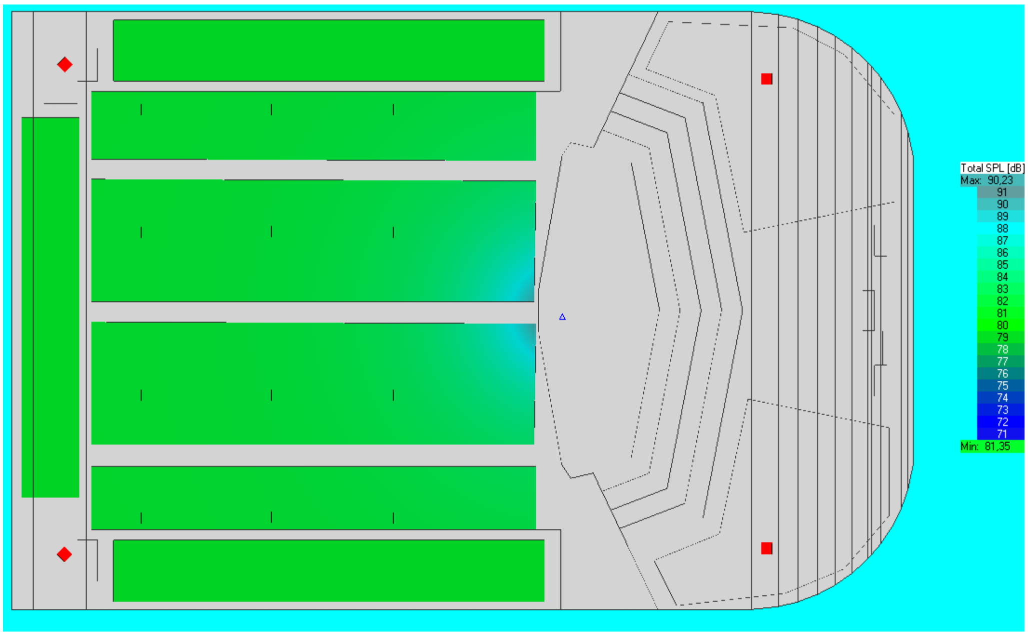


Figure 26. SPL at 1kHz

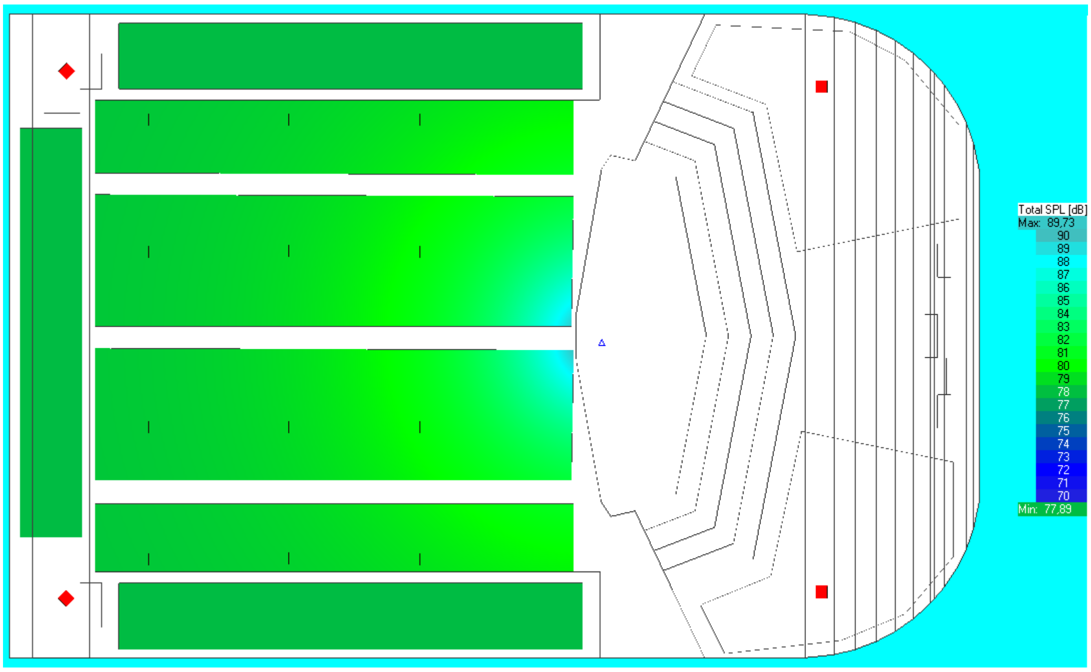


Figure 27. SPL at 8 kHz.