To the memory of
my grandfather Ömer Eken

ACOUSTICAL PERFORMANCE ANALYSIS
OF
BİLKENT UNIVERSITY AMPHITHEATER "ODEON"

A THESIS
SUBMITTED TO THE DEPARTMENT OF
INTERIOR ARCHITECTURE AND ENVIRONMENTAL DESIGN
AND THE INSTITUTE OF FINE ARTS
OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF FINE ARTS

By

Zühre Sü
May, 2004

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Fine Arts.

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ABSTRACT

ACOUSTICAL PERFORMANCE ANALYSIS
OF
BİLKENT UNIVERSITY AMPHITHEATER "ODEON"

Zühre Sü

M.F.A. in Interior Architecture and Environmental Design

Supervisor: Dr. Semiha Yılmazer

May, 2004

The aim of this study is analyzing the acoustical quality of Bilkent University Amphitheater ODEON by means of assessing the fundamental acoustical parameters for both speech and music. Defining the problems, specifying the causes of the problems and providing a foundation for the ongoing suggestions are within the frame of the analysis. The parameters such as reverberation time, early decay time, clarity, definition, lateral fraction, sound pressure level and sound transmission index are calculated by the computer simulation technique for their assessment to be carried out. Initially, the results of the simulation software are compared with the previous real-size measurements of Bilkent ODEON for the unoccupied condition of the amphitheater, in order to ensure the accuracy of the software. Proving to be a valid tool, the software namely ODEON Room Acoustics Program, is used in the calculations for the occupied condition of the amphitheater as a basis of the study. The results are evaluated from the acoustical design standpoint of a multipurpose hall, which are followed by the suggestions for the improvement of the existing acoustical performance of the amphitheater. Finally, the suggestions are supported through the simulation results of the new hall that is acoustically renovated.

Keywords: Room Acoustics, Acoustical Design, Multipurpose Auditoria, Echo, Reverberation Control, Acoustical Parameters, Acoustical Simulation, Amphitheater

ÖZET

BİLKENT ÜNİVERSİTESİ AMFİTİYATROSU ODEON'UN AKUSTİK PERFORMANS ANALİZİ

Zühre Sü

İç Mimarlık ve Çevre Tasarımı Bölümü

Yüksek Lisans

Tez Yöneticisi: Dr. Semiha Yılmazer

Mayıs, 2004

Bu çalışmanın amacı, konuşma ve müzik ile ilgili akustik parametreleri göz önüne alarak Bilkent Üniversitesi Amfitiyatrosu ODEON'un akustik performans analizini yapmaktır. Analiz kapsamında problemlerin tanımlanması, problemlerin sebeplerinin belirlenmesi ve getirilecek öneriler için temel oluşturulması hedeflenmiştir. Değerlendirmelerin yapılabilmesi için çınlama süresi, erken sönümleme süresi, berraklık, tanımlama, yan yansıma oranı, ses basınç düzeyi ve konuşma iletim indisi gibi parametreler bilgisayar benzetim tekniğiyle hesaplanmıştır. İlk olarak benzetim programının doğruluğunu belirlemek amacıyla, amfitiyatronun boş konumu için benzetim sonuçları Bilkent ODEON'da daha önceden yapılmış gerçek ölçümler ile kıyaslanmıştır. Geçerliliğinin kanıtlanmasıyla, ODEON Room Acoustics Program isimli benzetim programı, çalışmanın temelini oluşturan amfitiyatronun dolu konumu için yapılan hesaplamalarda kullanılmıştır. Sonuçlar çok amaçlı salonların akustik tasarım kriterleri baz alınarak değerlendirilmiştir. Değerlendirmeleri takiben, salonun şu anki akustik performansını iyileştirmek için bir takım öneriler getirilmiştir. Son olarak, getirilen bu öneriler salonun akustik açıdan iyileştirilmiş yeni haliyle yapılan benzetim sonuçları ile desteklenmiştir.

Anahtar Kelimeler: Oda Akustiği, Akustik Tasarım, Çok Amaçlı Oditoryum, Eko, Çınlama Süresi Kontrolü, Akustik Parametreler, Akustik Benzetim, Amfitiyatro

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NOMENCLATURE

C50, C80 (Clarity): The ratio of early sound energy to late sound energy arriving within 80 ms of direct sound to late or reverberant sound energy arriving later than 80 ms after the direct sound.

D50 (Definition): The ratio of the effective energy, which is the direct sound energy and the energy of reflections delayed with respect to the direct sound up to 50 ms, to the total energy in an impulse response.

EDT (Early decay time): The measure of the rate of a sound decay based on measuring the first 10 dB portion of the decay and multiplying it by 6 for corresponding with RT values.

G (Strength): The assessment of the total sound level at a closed volume, for a specific source and receiver configuration, by the comparison of the impulse response energy at this volume with the direct sound level at 10 m for the same source in an open field.

ITDG (Initial-time-delay gap): The time lapse at a listener's ears between the arrival of the direct sound and the first reflected sound of sufficient loudness.

LF (Lateral fraction): The fraction of lateral energy arriving between 5 and 80 ms after the arrival of direct sound compared to the total sound energy arriving at the listener within the first 80 ms of direct sound arrival.

RT, T30 (Reverberation time): The time required after stopping a sound source for the average sound energy density to decay by 60 dB from an equilibrium level.

SPL (Sound pressure level): The relative quantity, which is the ratio between the actual sound pressure and a fixed reference pressure, used in measuring the magnitude of sound.

STI (Speech transmission index): The single-number rating of transmission loss performance for a construction element tested over a standard frequency range.

1. INTRODUCTION

1.1. General

One of the main goals of architectural acoustics in the case of multi-purpose auditorium, which is the gathering place for speech and music performances, is to provide both the optimum speech intelligibility and the sound quality. The greatest challenge that the designer confronts at this point is to accommodate both unamplified music and unassisted speech within the same place, which is especially much difficult for the halls with seating capacities exceeding 2000. As it is known that good acoustics for speech and music are generally incompatible, either a compromise in between could be accepted or an electro-acoustical sound reinforcement system should be assisted.

At the earlier stages in the development of architectural acoustics, for the assessment of acoustical performances, the acoustical design of an auditorium was mainly focused on providing an optimum reverberation time. However, further technical developments and experiences of people have shown that it is not sufficient to consider only reverberation time. The acceptance of the limitation of reverberation time encouraged the development of new local criteria of acoustical quality, which were developed in studies of the correlations between objective acoustical parameters and subjective evaluations related to the diffusion of the sound field as well as to the details of sound reflections (Makrinenko 1).

The acoustical measures which are developed in recent studies of auditorium acoustics, besides reverberation time are including early decay time, clarity, definition, lateral fraction, sound transmission index, total sound level, intimacy, envelopment, warmth etc. If all the related measures are aimed to be supplied in an optimum range, than basically the design should maintain sufficient amount of early reflections which also provides a good reverberance, a significant proportion of them arriving from the sides and adequate sound levels throughout the hall with a good distribution of the sound field. These are all related with the geometrical details of the materials that are used inside the hall, reflective and absorptive surfaces, volume and geometry of the hall, besides the arrangement and the capacity of the audience seating.

With the search for new acoustical measures, the acoustical prediction techniques and acoustical measurement methods are also developed. The real-size measurements with the use of building acoustics measurement equipments and scale models are followed by computer simulations, which are more efficient considering time and cost than the earlier method of scale models of enclosures. This technique is extremely helpful, not only for the practical design of halls but also for getting more insight into the way of geometric details of a hall, the properties of its walls and the seating organization (Makrinenko 287). Besides the possibility of predicting the listening conditions at any desired position when the hall is completed, the computer simulation technique also enables the precautions to be taken at the design phase. By the way, the developments in the simulation technique gives a way for a new field of study under the subject of architectural acoustics, including analysis of the existing halls by the method of computer simulation as in the case of this research study.

1.2. Scope and Objective

The objective of this thesis is basically assessing the acoustical quality of Bilkent University Amphitheater ODEON by analyzing the above mentioned measures of auditorium acoustics, defining the problems, specifying the causes of the problems and secondarily making suggestions for improving the existing acoustical performance of the hall.

The methods used for the assessment of present condition of the hall are the real-size measurements and the computer simulation. Using both methods in the assessment enables to ensure the accuracy of the computer simulation results by making the comparison of this two. By the way, the second objective which is making recommendations on the acoustical improvement of the hall could be supported by using the method of computer simulation in its evaluation.

Accordingly, the thesis is presented in seven chapters. The second chapter following the introduction is the acoustical requirements in auditorium design, which includes the terminology that is directly related with the subject. These are subjective and objective criteria, which are discussed in the following parts as being the parameters examined both in the real-size measurements and in the computer simulation. Since Bilkent ODEON is a multi-purpose hall at which both the music and speech activities take place, the ways of meeting these requirements for both speech and music are also explained.

The third chapter with a name of Bilkent ODEON is comprising the collected data on the amphitheater. While mentioning of its history, the designers, and the design concept, the earlier project which is an open amphitheatre is also reminded. Moreover, the architectural and acoustical details including construction, materials, form and dimensions of the amphitheater are summarized under this chapter.

The fourth chapter is the real-size measurements at Bilkent ODEON. These measurements were made by one of the consultant engineering firms in Finland, when the hall is unoccupied. And, this is used for the comparison with the computer simulation results at the overlapping conditions of the amphitheater. In essence, this chapter is reviewing the earlier studies on the acoustics of Bilkent ODEON.

The fifth chapter is the computer simulation of Bilkent ODEON. The software used for the simulation is namely ODEON Room Acoustics Program. With the assistance of the software, all the parameters related with the auditorium acoustics are assessed for both unoccupied and occupied conditions of the amphitheater. The unoccupied condition is simulated in order to compare with the real-size measurements, and after ensuring the accuracy of the program the occupied condition is simulated as it is much realistic considering the time of performance. The results are compared and evaluated according to the terminological information given in the second chapter.

The sixth chapter is the acoustical correction of the hall. The suggestions for the acoustical improvement of Bilkent ODEON and their evaluations by using the simulation program are discussed under this chapter. The final chapter which is the conclusion is comprising a summary of the previous assessments of the present condition of the hall and the hall which is acoustically corrected.

2. ACOUSTICAL REQUIREMENTS IN AUDITORIUM DESIGN

The quality of acoustics for a room is basically evaluated by some objective and subjective requirements. These subjective and objective measures should have good correlations in between to be considered as reliable. The subjective acoustical quality of the audience area of an auditorium is determined by evaluations of the listening conditions for performers and listeners of music and speech, whereas objective parameters of the sound field could be derived from related equations, measurements with specific acoustic equipments or by computer assisted techniques (Makrinenko 23). The subjective measures which are corresponding to the objective ones are listed in the table below.

Subjective Measure	**Objective Measure**
Clarity	Early-to-late index
Reverberance	Early decay time
Envelopment	Mean frequency total sound level + early lateral energy fraction
Intimacy	Source-receiver distance and total sound level
Loudness	Mean frequency total sound level
Warmth	Bass level balance

Table 1. Objective measures corresponding to subjective attributes (Barron 189).

2.1. Subjective Criteria

Subjective requirements are, comprising the criteria which are basically depending on the ears interpretation of different measures. Design details in auditoria is ultimately determining subjective response. For the best acoustics it is necessary to optimize the various subjective attributes as far as possible with the design satisfying and supporting these conditions (Barron 42). The subjective attributes are basically intimacy, warmth, loudness, envelopment, reverberance, subjective clarity, diffusion, brilliance, ensemble (Lawrence 198), balance, blend, spaciousness (Marshall 100), spatial impression and dynamic response (Bradley 651). From these attributes first seven are discussed in detail which are related with the case in Bilkent ODEON.

2.1.1. Intimacy

In an auditorium acoustic experience should be sensed by the listener, which corresponds to the intimacy of one's degree of identification with the performance, whether one felt acoustically involved or detached from it. Musical presence, or intimacy in much technical terms corresponds to the time delay between when the original sound and the first reflected sounds reach to the listener. Optimally, this initial-time-delay gap should be in between 20 to 30 milliseconds (Dorris 85). For the subjective evaluation of intimacy, if music sounds as though played in a small room regardless of actual size should be determined. Accordingly, the evaluation for the hall could be vary from intimate to remote, or close to distant (Egan 147).

Intimacy is firstly affected by the optimal distribution of lateral reflections. These reflections can enhance the perception of source size and introduce a sense of spatial comfort and listening intimacy (Vassilantonopoulos 131). On the other hand, the first reflections, whether from the ceiling or lateral have significant influence on intimacy as the listeners are sensitive to these early reflected sound. In large halls especially, insufficient early reflections lead to a quite sound, which may be perceived as a lack of intimacy (Toshiyuki 228).

Other correlation with intimacy is the measured sound level that is averaged over frequency and the source-receiver distance, in other words the proximity to the performers. The hall should be designed for adequate sound levels with sufficient early reflections and later sound in order to maintain intimacy with a level of 0 dB as a minimum criterion. This task could be eased with shorter distances to the most remote seats, as good visual intimacy could also be provided by good sightlines and proximity to the stage (Barron 189).

2.1.2. Warmth

Warmth is commonly used to describe the sensation of a rich bass sound or the bass balance scale. In technical terms, it is the average of RT (Reverberation Time) at 125 and 250 Hz divided by RT at mid frequencies (500 and 1000 Hz), which should be range from 1.2 to 1.25 s for music performances. In order to evaluate warmth subjectively strength or liveness of bass compared to mid and treble frequencies should be listened. The results will vary from warm bass to cold bass or warm hall to dry hall. Higher values of bass ratio, indicate fullness of bass tone and acceptable in especially large halls (Maekawa108).

The sense of acoustical warmth is basically correlate with the sense of spatial impression, which is affected by the materials sound absorption qualities in low frequencies. The lower values enhance warmth, besides the coupled spaces and thick heavy enclosing surfaces. A reverberant volume under the stage platform can also be used to enhance warmth for the audience near the stage (Egan 155).

2.1.3. Loudness

This is the subjective dimension characterizing the loudness of the music source at fortissimo as related to the expected loudness at the seat. The subjective sensation of the sound strength or loudness is directly proportional to the objective sound level which is measured in decibels (Makrinenko 36). In order to evaluate loudness subjectively direct sound and reverberant sound should be evaluated during louder passages for comfort conditions and weaker passages for audibility. For speech the requirement is that it should be loud enough in compare to the background noise. In the case of symphonic music, most of the listeners respond enthusiastically to louder sound (Egan 147).

Loudness, which contributes to the definition of music, is affected by the volume, sound absorption, reflecting surfaces and shape of front end of the hall. The distance from stage to centre of main floor seats should not be more than 20 m and sightlines should be clear for an efficient loudness (Lawrence 98).

2.1.4. Envelopment

Envelopment refers to the degree of which the listener feels surrounded by the sound. The measure is directly related with the objective criteria namely lateral fraction. In subjective terms, the sense of envelopment is the spatial aspect of the perceived sound and it brings the sense of spaciousness. With a good sense of envelopment one has the sensation that the source broadens, that one is involved in a three-dimensional sound experience, and this associates with the best concert hall acoustics (Barron 41).

Like the other positive subjective characteristics of sound field described as warmth, loudness and intimacy, envelopment is also improved by the increasing lateralization of sound. Significant proportion of early reflections should arrive at listeners from the sides for adequate amount of lateral reflections. By the way, high values of envelopment could also be improved by the lack of early frontal sound and especially increases as the relative reflection energy of sound arriving from behind the listener increases (Edwards 133). In fact, all these reflection patterns should be considered at the design phase. For instance, continues reflecting side walls would create a good sense of envelopment. Accordingly, the sense of envelopment is best in the classical rectangular designs. Fan type lessens the lateral reflections, whereas reverse fan type is best for this purpose (Morimoto 109).

2.1.5. Reverberance

This subjective impression characterizes the duration of the sound decay process while listening to music. In technical terms, reverberation time at mid frequencies for fully occupied hall is corresponding to the reverberance or liveness of the room (Maekawa 108). In order to evaluate reverberance subjectively the persistence of sound at mid frequencies should be listened. The result will vary from live reverberance to dead reverberance. The longer the life of the sound, the better the orchestral music. Performance halls with a shorter reverberation time of 1.5 s or less are considered dry and best suited for amplified musical shows or speech (Dorris 85).

The reverberance is mostly affected by the volume of the hall, the sound absorptive material use, and the reflection patterns depending on the hall geometry. The sound absorption properties of the materials used inside the hall, by the way, is also affecting the general variation of reverberation time with frequency which should be in control (Lawrence 98).

2.1.6. Subjective Clarity

This is the property of sound to be clear in a closed space. The clarity is especially important for the musicians who are looking for hearing fine musical detail. Technically speaking, for a good subjective clarity initial-time-delay gap should be less than 20 ms. In order to evaluate clarity subjectively the beginnings of musical notes should be listened and the degree to which individual notes are distinct or stand apart should be observed. The results will vary from clear or distinct sound to blurred or muddy (Egan 149).

Subjective clarity is basically affected by the early reflections. The increase in early reflections enhances the sense of clarity and if the reflections arrive from the side they also provide a desirable sense of envelopment. Another way of maintaining a clear sound is keeping the length to width ratio of the hall smaller than 2 or else suspended sound-reflecting panels should be used. Deep under balconies are drawbacks for the measure that should be avoided, and the use of overhead reflectors for providing early reflections would be useful for this purpose (Barron 406).

2.1.7. Diffusion

Most of the sound energy we receive in enclosed spaces has been reflected from wall and ceiling surfaces. Sound is reflected between the room surfaces, until its energy is removed by absorption. In closed spaces the reverberant sound, which is coming to the listener from all these surfaces with different directions, will provide a proper sound decay incorporating with a diffused sound field and a uniform sound level distribution (Çalışkan). The diffused sound field implying a good diffusion could be evaluated subjectively by listening the envelopment of terminal sounds or feeling of immersion in sound, in order to compare conditions with eyes open and closed. If satisfactory diffusion has been achieved, listeners will have the sensation of sound coming from all directions at equal levels (Egan 147).

For a good diffusion, first of all, the sufficient amounts of diffusing surfaces should be used inside the hall especially for music purposes. The diffusing surfaces such as the wall and ceiling irregularities near musicians, for instance, provide useful early inter-reflection of sound energy. Large-scale wall and ceiling surface irregularities and quadratic residue diffusers enhance the quality of diffusion, whereas flat surfaces should be avoided which can cause harsh or glaring listening conditions for music. Coffering the ceiling and constructing deep side-wall niches and plasters could also help to diffuse sound throughout the hall (Maekawa 108).

2.2. Objective Criteria

Objective measures offer an intermediate description between design and subjective effect. According to the behavior of sound in rooms the design creates a sound field at the listener's position, which can be described in objective acoustic terms. There are two basic independent factors that to some extent the objective criteria depend on. These are room volume and total surface absorption (Barron 42). The objective parameters discussed under this section in sequence are reverberation time, early decay time, clarity, definition, lateral fraction, strength and initial-time-delay gap.

2.2.1. Reverberation Time (RT)

In a very rough human terms, Everest defined reverberation time as, the time required for a sound that is loud enough to decay to inaudibility (111). The general scientific description for the reverberation time is that the time required after stopping a sound source for the average sound energy density to decay by 60 dB (one-millionth of its original value) from an equilibrium level. Since the time of W.C. Sabine in 1900 studied the phenomenon reverberation time, it has been used as the most important indicator of the acoustic characteristics or the auditory environment of a room (Maekawa 18). Figure 1. is illustrating the definition of the reverberation time with a sample decay curve.

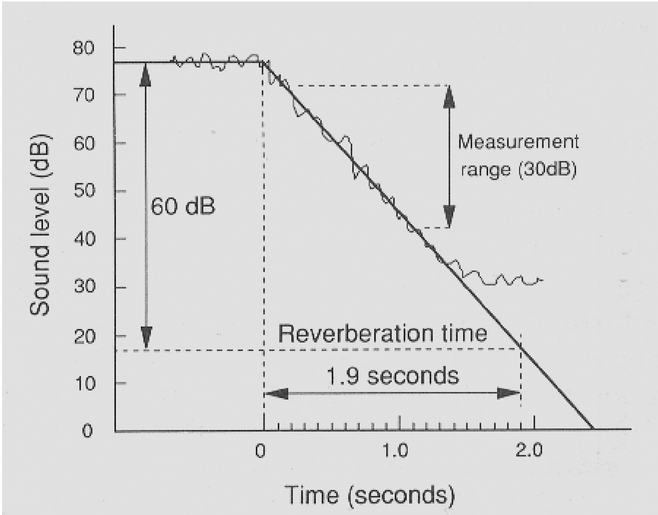


Figure 1. Reverberation time definition with a sample decay. The slope of the decay is, in practice measured between -5 dB and -35 dB of the initial level (Barron 27).

There are three main reverberation time formulas. The first one is the Sabine's formula which is applicable to live rooms. The second and the third formulas are the Eyring's formula and Millington&Sette formula. These last two reverberation time formulas are applicable to dead rooms. For all these three reverberation time formulas to be applicable, the sound field should be a diffuse field (Maekawa 81). These three are in following as:

a) Sabine's Formula;

T = (0,163 V) / A in seconds,

Where, A = the equivalent sound absorption area in m² (= $\sum S\alpha_{av}$)

$\sum S\alpha_{av} = S_1\alpha_1 + S_2\alpha_2 + \ldots + S_n\alpha_n$

V = the volume in m³

S = the surface area in m²

α = sound absorption coefficient (Cremer 343).

b) Eyring Formula;

$\alpha_1 \approx \alpha_2 \approx \alpha_3 \approx \ldots \approx \alpha_n,$

$T = (0{,}163\ V) / [\ -S\log_e (1 - \bar{\alpha})\ ]$ in seconds. Where, $\bar{\alpha} = \sum S\alpha_{av} / S$

c) Millington & Sette Formula;

$\alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \ldots \neq \alpha_n,$

$T = (0{,}163\ V) / [\ \sum -S_n \log_e (1 - \alpha_n)\ ]$ in seconds (Maekawa 78).

For music perception, reverberation adds to the fullness of tone, richness of bass frequencies and blended sound. So in halls for music, it is desirable that reverberation time rises towards low frequencies. A relative reduction of low frequency sound pressure level and the sensation of a lack of low frequencies result in the reduction of spatial impression. On the other hand, a relative reduction of the high frequency level results in a reduction of clarity (Makrinenko 46). If the reverberation time is too long, than it could be masked by an earlier louder sound and thus become inaudible. By the way, with too short a reverberation time, the sound quality becomes too stark, like listening in the open air. The proper reverberation times for mid frequencies (500 and 100 Hz) and for different activities are best illustrated in Figure 2.

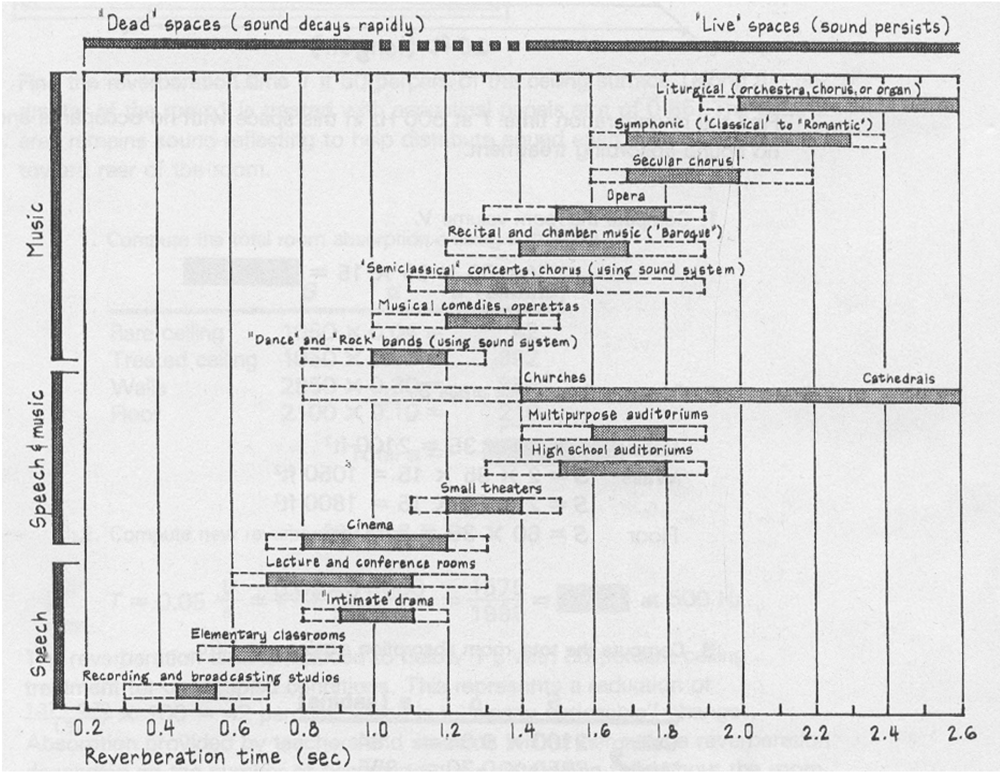


Figure 2. Optimum reverberation times for different activities (Newman 696).

2.2.2. Early Decay Time (EDT)

In very rough terms, EDT is the sensation of RT. Technically, it is the measure of the rate of a sound decay, expressed in the same way as a reverberation time (RT), based on measuring the first 10 dB portion of the decay and multiplying it by 6 for corresponding with RT values. This measure has been shown to be better related to the subjective interpretation of reverberation time, and more critical in setting the acoustical quality of a hall for music (Barron 42). As EDT involves the first 10 dB portion of the decay, it is sensitive to room geometry, in particular to strong early reflections which reinforce sound in the first 100 ms. Therefore it depends particularly on the measuring position and it is sensitive to details of this geometry. In large halls, for instance, the EDT can vary spectacularly which shows the remoteness of the surfaces (Templeton 61).

Firstly, for good acoustical conditions the EDT should not differ from the Sabine RT more than 10%. EDT/RT ratio at mid frequencies is a valuable parameter to consider and that it constitutes a measure of the directedness of a concert hall. In a hall with a highly diffuse space, where the decay is completely linear the ratio is unity. Values of the ratio are more often less than unity in halls with surfaces which direct early reflections onto the audience (Barron, JASA 2230). In very good to excellent halls, the EDT at mid frequencies is about 0.5 s longer than RT at mid frequencies. With a shorter EDT, satisfactory reverberance can be obtained by having a longer RT than normal. The suggested optimum range for EDT for mid frequencies is from 1.7 to 2.3 s to provide reverberance for concert use, and from 1.4 to 1.9 s for multipurpose use (Hidaka 342).

2.2.3. Clarity (C80)

Clarity or the early-to-late sound index is the quality characterizing the separation in time of the sounds of individual instruments or groups of instruments, which should be adequate especially for the performers in hearing the musical details of these different instruments and themselves. The technical description for the clarity is that the ratio of early sound energy arriving within 80 ms of direct sound to late or reverberant sound energy arriving later than 80 ms after the direct sound (Makrinenko 36). The formula for the objective clarity is developed as;

$$C_{80} = 10 \log \left\{ \frac{\int_0^{80ms} g^2(t)dt}{\int_{80ms}^{\infty} g^2(t)dt} \right\} \text{dB (Kuttruff 191).}$$

A subdivision of sound into an early and late part originates from the characteristics of our hearing system. The early part contributes to clarity and definition, while the late reverberant part provides an acoustic context against which the early sound is heard. The relevant time interval for early sound with music as mentioned is 80 ms, while it is taken as 50 ms for speech. The choice of the boundary between the early and late energy in the clarity index is attributed to the fact that reflections with a delay of up to 80 ms enhance the clarity of musical sounds. Moreover, the time for the build up vibrations in most musical instruments is about 100 ms. This means that during the first 80 ms, most of the energy of vibrations will arrive at the listener and permit him/her to properly identify the tone being played (Makrinenko 38).

If a good clarity is to be maintained than sufficient early reflections, which includes both the direct and reflected sound, should be provided. Clarity and spatial impression can also be simultaneously enhanced by increasing the energy of lateral reflections in the delay range from 25 to 80 ms. A higher objective clarity than the suitable is due to the reflector directing a lot of sound energy on to the audience. By the way, the sound levels of all components decrease with distance, but the early sound level decreases faster than the late, so expected objective clarity also decreases as one moves away from the stage (Barron 63).

In the case of clarity, the ear’s temporal response to bass frequencies (125 and 250 Hz) is slight so of minor interest and the mid frequency mean value (500, 1000 and 2000Hz) is used. For a speech oriented hall, positive values of clarity are desirable as they result in a crisp acoustics, which is suitable for classic music and some operatic use, but will not provide a suitable setting for romantic and choral works which are enhanced by a greater reverberance and requires a clarity between 0 to -2 dB (Templeton 62). The acceptable values of clarity for different rows are listed in the Table 2.

Quality steps	C80 values, dB	
	Front rows	Back rows
Good	From +3 to +8	From 0 to +5
Acceptable	> +8 and -2 to +3	From +5 to +9
Unacceptable	< -2	> +9, < -5

Table 2. Optimum values of C80 for front and back rows of a hall (Makrinenko 38).

2.2.4. Definition (D50)

One of the earliest attempts to define an objective criterion of what may be called the distinctness of sound, obtained from the impulse response is named as definition which is originally 'Deutlichkeit'. This is the measure derived from the ear's response to consecutive impulses and characterizes the ratio of the effective energy to the total energy in an impulse response. The effective energy includes both the direct sound energy and the energy of reflections delayed with respect to the direct sound by up to 50 ms. The definition formula is accordingly proposed as;

$$D_{50} = \frac{\int_0^{50ms} g^2(t)dt}{\int_0^{\infty} g^2(t)dt}$$ (Kuttruff 190).

There is a good correlation between definition and speech intelligibility. For a good auditoria with good definition its values should have higher values basically for speech to be intelligible. The opposite will be evaluated as an auditoria with poor definition conditions, where the details of a speech could not be separated properly. The values should not exceed 0.25 for music purposes whereas, they should not be lower than 0.15 considering the speech activities (Templeton 62).

2.2.5. Lateral Fraction (LF)

The lateral fraction, in other words the objective envelopment, defines the relationship between a sense of spatial impression or the arrival of reflected sound from sidewalls relative to the listener. In technical terms, it is the fraction of lateral energy arriving between 5 and 80 ms after the arrival of direct sound compared to the total sound energy arriving at the listener within the first 80 ms of direct sound arrival (Templeton 62). Accordingly the formula for the lateral fraction is proposed as;

$$LF = \frac{\int_{5ms}^{80ms} g^2_F(t)dt}{\int_{0}^{80ms} g^2_0(t)dt}$$ (Barron, *Late Lateral* 191).

A sense of envelopment is almost solely produced by late lateral reflections and late lateral sound level which is linked to the total acoustic absorption in halls. The values for lateral fraction, consequently, is high in small halls and low in large ones, similarly higher in rectangular shaped and reverse-fan shaped halls, and poor in fan shaped halls (Barron, *Applied Acoustics* 200).

2.2.6. Strength (G)

Strength, or total sound level, is directly related to the judgment of loudness which is considered principally at mid frequencies. In objective terms, the total sound level at a closed volume, for a specific source and receiver configuration, could be assessed by the comparison of the impulse response energy at this volume with the direct sound level at 10 m from the same source in an open field (Çalışkan). And, the formula for the parameter is proposed as;

$$G = 10 \log \left\{ \frac{\int_0^\infty g^2(t)dt}{\int_0^\infty g^2{}_A(t)dt} \right\} \text{dB (Hidaka 353).}$$

The total sound received, which should exceed the direct sound level at 10m, is composed of two components; the direct sound which decreases 6dB for every doubling of distance, and the reflected sound which has traditionally been assumed to be constant throughout the space. Almost all the listeners receive more energy which is reflected rather than direct, so the room's reflection pattern has an important role on the amount of total sound level. Accordingly, the acoustical characteristics of the room, the total acoustic absorption and the distance from the source are all affect the results. Another important aspect influencing the total sound level in a room is the sound energy being generated. Both for the speech and music the sound level is very important, which is highly dependent on the performer and the orchestra (Barron 18).

2.2.7. Initial-Time-Delay Gap (ITDG)

The initial-time-delay gap is the time lapse at a listener's ears between the arrival of the direct sound and the first reflected sound of sufficient loudness (Beranek 789). The following figure is illustrating the relation of ITDG with direct and first reflected sound.

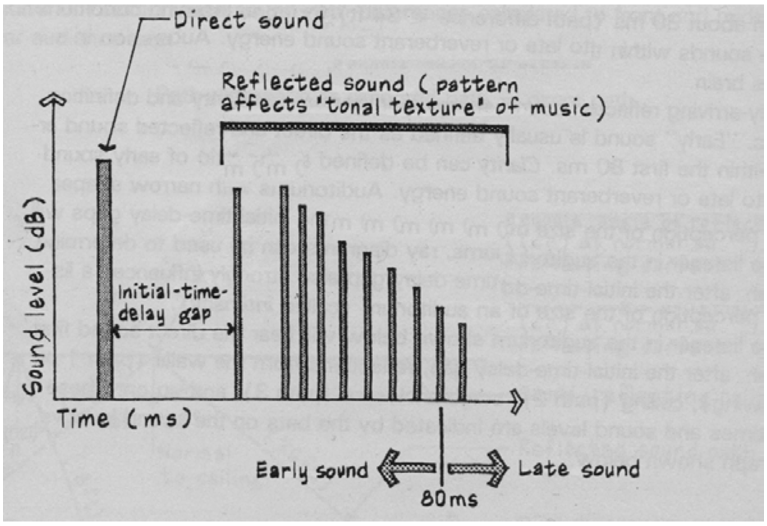


Figure 3. Impulse response illustrating initial time delay gap (Egan 99).

The initial time delay gap is considered to be a measure of perceived acoustic intimacy, as it strongly influences a listener's perception of the size of an auditorium. The best-liked concert halls have short initial-time-delay gaps of 20 ms or less, which provide useful reinforcement of direct speech sounds. Auditoriums with narrow shapes support these direct and early reflected sounds and smaller values of initial-time-delay gaps could be obtained (Barron 39).

The acceptable values for concert halls;

EDT	(1.8)-(2.2)
Objective Clarity	(-2)-(+2) dB
Objective Envelopment / Early lateral energy fraction	(0.1)-(0.35) for concert halls greater than 0.35 for other purposes
Total sound level	greater than 0dB

Table 3. Optimum ranges for objective parameters for music use (Barron 61).

2.3. The Nature of Speech and Music Sounds

Both music and speech consist of brief sound events which are separated by silence and they both occupy similar frequency ranges. These similarities imply that the physical behavior of sound in a room is virtually same for the both. The differences occur in the way the physical sound waves are interpreted by our ears. In the case of music, harmony and tonality are fundamental aspects. With speech, tone is only used for phrasing and recognition purposes (Barron 11).

In the case of speech, intelligibility is supreme and this is known to be associated with the proportion of energy which arrives early, both in the direct sound and early reflections. The corresponding quality for music is clarity and definition which can be related to a similar energy proportion. The relative strengths and durations of concurrent speech sounds or notes are of supreme importance for room acoustics. They determine the degree to which sound reflections can be tolerated without intelligibility or clarity being undermined (Barron 13).

The aspect of speech and music influencing room acoustics is the temporal one. The individual sound events with speech are syllables and a typical speaking rate is five syllables per second, whereas music is much more flexible. The musical sounds witch pitch depend on resonance for their generation. A small amount of energy is supplied by a resonating musical instrument which maintains oscillations at a particular frequency. Individual speech sounds or musical notes have particular amplitudes and durations. They both depend on contrasts of soft and loud sounds with the dynamic range. (Barron 13). The dynamic range of speech is about 42 dB and it is covering from 170 to 4000 Hz, about 4.5 octaves. On the other hand, music uses a much greater proportion of the full auditory area of the ear. The music area has a dynamic range about 75 dB and a frequency range of 50 to 8000 Hz, about 7.5 octaves. This span is sufficiently large when compared to the 10 octave range of human ear (Everest 88).

Human speakers are omni-directional at low frequencies and become more directional at high frequencies. The reason for this directivity is the finite size of the mouth and the location of the mouth in the head. The mouth is smaller relative to the wavelengths of most speech sounds and the shadowing by the head is found to be the major concern. By the way, the male voice contains more low-frequency energy than the female voice. The lower frequency contains less intelligibility information but it is louder. At 500 Hz the energy is predominantly due to the vowels at which there is a small difference between the level in front and behind the speaker. At 4 kHz much of the energy is associated with the consonant sounds and levels behind the speaker are substantially decreased. The vowel sounds have fairly definite spectral characteristics and contain the major part of the energy audible in connected speech.

On the other hand, consonants tend to have short duration and less energy although they contain more information. The most important speech frequency range is from about 1000 to 4000 Hz (Lawrence 83).

In the case of music, the timbre or the sound character of different musical instruments is related to its frequency spectrum. The fundamental of first harmonic is the lowest frequency. The higher frequencies are simple multiples of the fundamental frequency, which are known as the second, third harmonic etc. Our ears interpret the mixture of frequencies in terms of its pitch which is determined by the lowest frequency normally, while the relative strength of the harmonics characterizes the sound quality or timbre of the instrument. In design terms, the greater significance of high frequencies does have a compensating advantage over lower frequencies that useful reflecting surfaces do not need to be too large (Barron 11).

2.3.1. Acoustics for Speech

The satisfaction for speech is much simpler than for music. If speech is intelligible and background noise is not intrusive, dissatisfaction is unlikely. For any auditorium, concern for reverberation time and the elimination of echoes are standard requirements. The optimum RT values for speech is around 1s at mid frequencies (500 and 1000 Hz) with sufficient loudness which does not rise in the bass (Lawrence 116).

Adequate early reflections are important for speech, so surfaces must be oriented to provide early acoustic reflections. Useful sound reflections for speech are those which come from the same direction as the source and are delayed by less than

30 ms. In design terms, enabling satisfactory speech conditions could be enhanced by a good direct sound design, and the first condition of a good direct sound is seating the audience closer to the stage (Egan 88).

Speech intelligibility is the basic parameter of the acoustical qualities of rooms for speech. In the cases of this requirement not to be satisfied, such as the halls with seating capacities exceeding about 500, a sound-reinforcing system to augment the natural sound source to listener should be provided (Egan 88).

2.3.1.1. Speech Intelligibility

The subjective requirement for speech is that it should be intelligible. The definition for speech intelligibility is simply the percentage of correctly received phrases. Good intelligibility can be provided by a sufficient high level of speech, low noise levels, short reverberation times, and reflection patterns with strong early reflections and without strong late arriving reflections (Makrinenko 25).

Acoustic measures of speech intelligibility have concentrated on two concerns which are the signal-to-noise ratio and the impulse response. The speech sound must be loud enough relative to the background noise, which is defined as signal-to-noise ratio. This signal-to-noise group is evaluated by the articulation index. In enclosed spaces incoherent late reverberant speech sounds take the place of noise. Long reverberation times reduce the intelligibility of speech in the same way noise masks speech signals. In a room the signal or speech level is a function of the source-receiver distance, the speaker orientation and the room reflections, in addition to individual speaker differences. Therefore, intelligibility varies within the auditorium (Egan 88).

Turning to the impulse response measures, the early energy fraction come into the scene, which is based on a subdivision between useful and detrimental energy. This early energy that is obtained form the impulse response can be used as a predictive tool for measuring speech intelligibility. In the case of early energy fraction, the division occurs abruptly at 50 ms after the direct sound. For speech to be intelligible requires this early proportion to be high; in design terms strong early reflections should be provided at the seats especially located more than 8 meters from the sound source. The comparable concern for music is definition or clarity (Barron 18).

In a space for speech the mid frequency RT should be in between 0.5 to 1 s. If the RT values are higher than the optimum range, than extra absorbent can be added in order to reduce this excessively live space, as for speech a dead space will have better intelligibility, which depends heavily on consonant sounds. For speech, keeping the reverberation characteristics constant with frequency is also important; arise in the bass undermines intelligibility. The stationary sound level at low frequencies should be satisfied by suitably applying sound absorbers to the necessary locations of the rooms used for speech (Beranek, *Acta Acustica* 496).

2.3.1.2. Speech Transmission Index (STI)

The STI has been strongly promoted for predicting speech intelligibility through impulse response. It accommodates both the signal-to-noise ratio and the impulse response aspects which affect intelligibility. The idea behind this measure is that for good speech intelligibility the envelope of the signal should be preserved. It allows for the different contributions of the various frequency bands to speech quality, and also for the mutual masking between adjacent frequency bands occurring in our hearing organ (Kuttruff 195).

An objective evaluation method, which is called the rapid speech transmission index (RASTI) and known as the shorter approach of STI, has been developed to electronically measure speech intelligibility in rooms in the same way of STI. This method uses a modulated test signal spectrum to simulate speech at 500 and 2000 Hz (Egan 111). Accordingly, the relation between STI (RASTI) and intelligibility is expressed in the Table 4.

Quality Score	STI (RASTI) value
Bad	0 to 0.32
Poor	0.32 – 0.45
Fair	0.45 – 0.60
Good	0.60 – 0.75
Excellent	0.75 to 1.0

Table 4. Relation between scores of speech transmission quality and STI (RASTI) (Beranek 623).

2.3.2. Acoustics for Music

A major criterion for listening to music hall is that the audience should perceive the difference between hearing the sound from loud speakers at home or being present at a live performance. An acoustical design of an auditorium for speech causes no serious difficulties, whereas it is much more difficult to acoustically design rooms intended for musical performances. The acoustical requirements for speech and music are not only different, but to a considerable extent opposite (Lawrence 98).

Intelligible speech depends on a strong early sound relative to the late reverberant sound. For music the energy balance should be shifted towards the later sound which is a major objective consequence of having a longer reverberation time. In halls intended for musical performances long reverberation times should be provided to enhance the spatial impression of music. When designing the reverberation time, volume and height of a hall an optimum ratio between these parameters is observed as;

$(V/T_{500})^{1/3} / h_{max} = 1.25$, where T_{500} is the reverberation time of the occupied hall at a frequency of 500 Hz and h_{max} is the maximum height of the hall in meters (Makrinenko 122).

The auditorium volume should be chosen to provide a suitable reverberation time that there are adequate early reflections, with a sufficient proportion arriving from the side for achieving both high clarity and reverberance. These early reflections in concert halls contribute to the sense of both clarity, intimacy and loudness and if they arrive from the side to the sense of envelopment as well. There should also be an amount of sound arriving to the listener from behind. Music in rooms with appropriate reverberation times sounds full-toned, live and blended, whereas in rooms with too much reverberance, it sounds muddy and indistinct (Egan 155). The satisfactory level of sound or loudness which is referred as dynamic range by musicians, definition of music perception, intimacy, and appropriate tonal balance and texture should be achieved, besides a good reverberance, clarity and envelopment in the auditoriums which are primarily used for music performances. The signals at the two ears should be uncorrelated, and there should be no perceived echoes. Moreover, an ambient level inside a concert hall should not exceed 25 dBA (Lawrence 195).

The early reflections from lateral directions could be enhanced by profiling the walls and ceilings, and introducing suspended reflectors. High ceilings are preferable for concert halls. All walls should be sound reflecting and ceilings should be diffusing in order to improve audibility of lateral sound by diminishing the strength of ceiling reflections. For both acoustic and visual reasons the distance to the furthest seat should not significantly exceed 40 meters. Besides, the ratio of height to width of a hall should be greater than 0.7 and the ratio of length to width should be smaller than 2 (Egan 154). Considering these ratios, the rectangular plan generates many reflections and established a considerable reputation for its acoustics, while the opposite type can be said that the fan-shape. The elongated hexagon, on the other hand, offers a compromise with the visual advantages of the fan shape and the acoustic advantages of the reverse splay. The situation of seats being remote from reflecting surfaces can be seen in fan-shape plan which is inappropriate for concert use (Barron 190).

2.3.3. Meeting the Requirements of both Speech and Music

Multi-purpose auditoria is a recent phenomenon that has arisen from the need to optimize the usage of auditoria in order to supply more flexible facilities. These are the most common category of room, which are sometimes called as universal halls, that the problem of combining various types of programs occurs in using the space both for speech and music activities. It is a common observation that good acoustics for speech and music are generally incompatible. Unless the design requirements can be provided, than some compromises should be made (Barron 28).

A major dilemma in design of multi-purpose spaces exists for reverberation time. The reverberation time must be long enough to properly blend sounds, and short enough to provide sufficient separation of successive sounds for intelligibility, whereas each acoustic use of a hall has an optimum reverberation time associated with it. So, in multipurpose halls a comparatively short reverberation times should be provided. In large multipurpose halls controlling this reverberation time and providing audience seats with early reflections are actually difficult without electronic assistance (Makrinenko129).

In design terms, the internal surfaces of a multipurpose hall should be constructed so that some of them direct strongly early reflections towards listeners, which increases clarity, and the others create non-directional scattered reflections of sound which increases the diffusivity of the sound field. This is achieved by having two types of surfaces in the hall. From these two types the surfaces which do not provide early reflections should be divided into smaller parts to provide diffuse reflections. Other type of surfaces, which are in particular adjoining the stage, should not so heavily divided into parts. As in halls for music, early reflections from the side walls adjacent to the stage are desirable in multipurpose halls, which enhance both clarity and spatial impression. Strong overhead reflections are considered undesirable for music, but reflection direction is of no concern with speech. Additional lateral reflections therefore, which arrive early enough to enhance speech intelligibility, could be viewed as beneficial for both uses. The optimum reverberation times and some other attributes for different activities are given in the Table 5.

	Concert hall	Opera house	Drama theater
Reverberation time (s)	1.8-2.2	1.3-1.8	0.7-1.0
Diffusion	Some	Yes, around stage	Not needed
Surfaces to provide early reflections	Yes	Yes, especially for singers	Yes, especially from above
Preference for early reflections from side	Yes	Some preference for orchestral sound	No preference
Balcony design	$D \leq H$	$D \leq 2H$	$D < 2.5H$
Maximum distance of audience from stage (m)	40	30	20

D = horizontal depth of overhung seating, H = height of opening.

Table 5. Some features which distinguish the acoustical design of concert halls, opera houses and drama theaters (Barron 404).

Besides the reverberation times given in the Table 5. for different activities, the reverberation time (T) for a multi-purpose hall is given as 1.4 to 1.9 s at mid frequencies, 1.3 RT at 125 Hz, and 0.8 T at 4000 Hz (Egan 125).

In a multi-purpose hall, the reverberation time and other acoustical qualities can be varied by changing the volume, the audience seating area, additional absorption, or the variable diffusion and reflection. For physically variable or flexible acoustics these different methods of design are explained below.

1) Variable auditorium volume; changes in volume enables changes in reverberation time as well. Modest volume changes in some buildings have been incorporated by using reverberant chambers around the perimeter, which are coupled acoustically to the main volume. Besides, mechanically operated ceilings have been developed that can be raised or lowered to serve the needs of various types of events. And finally, the decrease of the volume could also be achieved quite simply by installing movable partition in a remote part of the hall. However this is an expensive method and usually restricts the design possibilities of the architect (Makrinenko 132). Optimum volumes for specific purposes are listed in the Table 6.

Optimum Volume (m^3/occupant)			
Performance	Minimum	Recommended	Maximum
Theatres	2.5	3	4
Rooms for speech	-	3	5
Opera houses	4	5	6
Concert halls	8	10	12
Churches	6	10	14
Multi-purpose halls	6	7	8

Table 6. Optimum values for performance spaces (Templeton 56).

2) Changing the audience area; another way of reverberation time change is the alteration of seating capacity of the hall. If the seating is upholstered then in principle by removing seating the reverberation time will be extended (Barron 346).

3) Variable acoustic absorption; this method enables sound pressure changes and reverberation time changes. The area of the adjustable absorption must be comparable to that of the audience area which makes the technique only appropriate to smaller halls. In large quantities of absorption there is a risk of quiet sound and killing of vital reflections. Variable sound absorbers are including retractable sound-absorbing curtains, banners, sliding facings, hinged panels and rotatable elements (Egan 135).

Reverberant concert halls can be made deader for speech by dropping banners or drapes up to 15%, which will improve speech intelligibility in the hall, while small or dead halls could be enlivened acoustically by electronic means. For the maximum absorption both the weight and porosity of the banners must be optimized, which are generally most effective at mid frequencies (Templeton 62). As the banners increase the total absorption and makes the reflected sound quieter, in a large hall this might be undesirable to squander acoustic energy in this way, which may also obscure valuable early reflections. Use of both a volume change and a total absorption change offer the chance of less extreme degrees of each (Barron 346).

4) Variable acoustic reflectors; in multi-purpose halls, movable sound-reflecting walls and ceilings are often installed around the stage as an orchestra shell, by which the sound energy is reflected back to the players rather than absorbed in the backstage, creating better ensemble and providing improved listening conditions for the audience. Large acoustic canopies sling over the platform could also adjust the acoustics for different sized events (Templeton 62).

Another type of variable reflectors are the ones with one side absorptive and the other side reflective. These can be positioned appropriately according to the purpose. A good example can be seen in the case of UFO shaped event hall in Kobe Fashion Plaza, which has got focusing problems due to the circular form of the hall both in plan and sections as in the case of Bilkent ODEON (Takatsu 297).

5) Variable diffusion; a change in diffuseness of a surface carries less impact than change in absorption or orientation. So large areas would have to be changed for audible effect (Barron 344).

An alternative way of enabling the conditions for multi-purpose use is to choose a compromise RT adequate for both speech and music. This is easier in a smaller hall as a short RT is more acceptable for music in smaller spaces, but not acceptable in larger ones. So, the final choice for the variable acoustics is through electronic means. These kind of solutions necessitate complex and expensive devices, highly qualified service personnel, and make it impossible to use the hall for musical programs with natural audibility of the orchestra, however it is inevitable for the acoustics of halls with seating capacity greater than 3000. In these larger halls the optimal speech communication could not be satisfied without an electronic assistance, as the RT increases linearly with volume and being not moderated by increase of total absorption (Vassilantonopoulos, *Virtual Acoustic* 604).

2.3.4. Acoustical Defects

As a listener the direct sound is the first thing one hears, which travels in a straight line from the source. This is followed by a series of early reflections from the ceiling, side walls etc. Reflected sound has to travel further and so will arrive later. It will not be as loud as the direct component if some focusing of the reflection does not occur. This response can be represented as a diagram of sound level against time, which is known as an impulse response or echogram. The various quantities including intelligibility, clarity and sound level can all be derived from impulse response (Barron 18). The Figure 4 is illustrating a sample room and its impulse response graph.

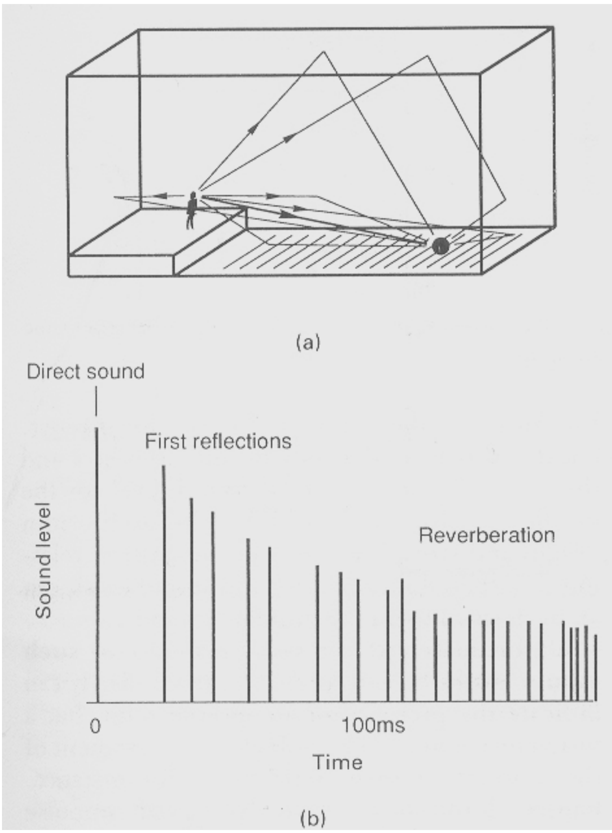


Figure 4. Sound rays in rooms. (a) The direct and first reflection paths; (b) sound level against time for a short sound as received by the listener (Barron 17).

The received sound can be divided into three components; the direct sound, early reflections and late reverberant sound which is after about 100 ms. In acoustic terms; the early components of sound principally consist of discrete elements; the direct sound and a few early reflections. However with the late sound, the density of reflections which is the number arriving in time intervals such as 150-160 ms after the direct sound becomes so high that detailed paths are of little significance except in the case of echoes. For the late sound the average behavior with time, its level and gross directional distribution are important such as in the case of reverberation time (Barron 61). The acoustical defects are generally resulting from different relations of these early and late, direct and reflected sounds and their energies, which could be easily defined from the impulse response. The acoustical defects are basically, echo, flutter echo, sound foci, sound masking, room resonance (Holden 37), coloration, degraded localization of the sound source and interfering noise. From these defects echo, sound foci, sound masking, and coloration are discussed which are the defects observed in the acoustical analysis of Bilkent ODEON.

2.3.4.1. Echo

An echo is the distinct repetition of the original sound, which is sufficiently loud to be clearly heard above the general reverberation and background noise in a room. For speech signals, echoes can be perceived when the time intervals between the direct and reflected sounds are greater than 50 ms corresponding to a path length difference of 17 m, for music this limit is about 50% higher (Egan 101). An example of an echo in an impulse response graph is given in the Figure 5.

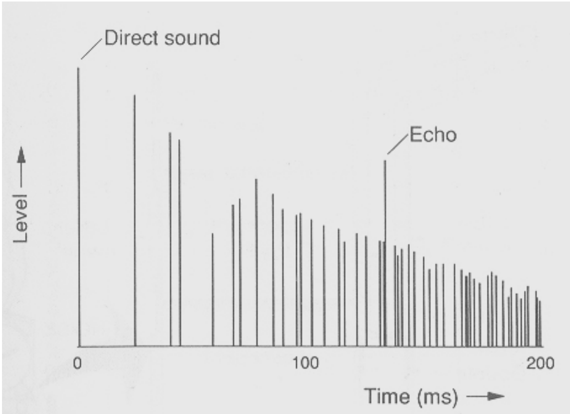


Figure 5. Impulse response with an echo (Barron 25).

The word echo is only used for a reflection which is heard as a discrete event and an intelligible repetition. So, an echo should not be confused with reverberation which is unintelligible. The audibility of an echo depends upon the objective parameters including the reflection time delay, intensity relative to the direct sound and type of sound signal. Echoes which are noticeable for a speech signal may not interfere at all when music is played. On the other hand, sufficiently intense intermediate reflections, arriving between the echo and direct sound, result in a reduction of the effect of the echo (Makrinenko 47).

An echo to be perceived requires either reflection from a large surface by a path simpler than other reflections of the same delay, or reflection involving focusing. In the first category the frequent cause of echoes are the reflection of the back wall or back wall and the adjacent soffit, these are only heard as echoes in large rooms. The second category of focused echoes are a common problem in halls with domes or barrel-vaulted ceilings, or in fan-shaped plans with curved rear walls. In auditoriums, sound-reflecting flat or concave rear walls and high or vaulted ceilings are potential echo producers. Actually, the most common cause of serious echo problems are that kind of concave surfaces which concentrate the reflected sound in a small area of the hall. If the center of the curvature of such a surface is near the location of the sound source, than the concentration would be strong (Makrinenko 86).

Owing to this acoustic defect, speech articulation decreases considerably since speech sounds consist of successive short sounds, and the performance of music becomes difficult because the rhythm is no longer easy to follow. So, echoes damage room acoustics seriously (Maekawa 84). The sound level and time delay graph is given to illustrate the region of disturbance owing to echo in the Figure 6.

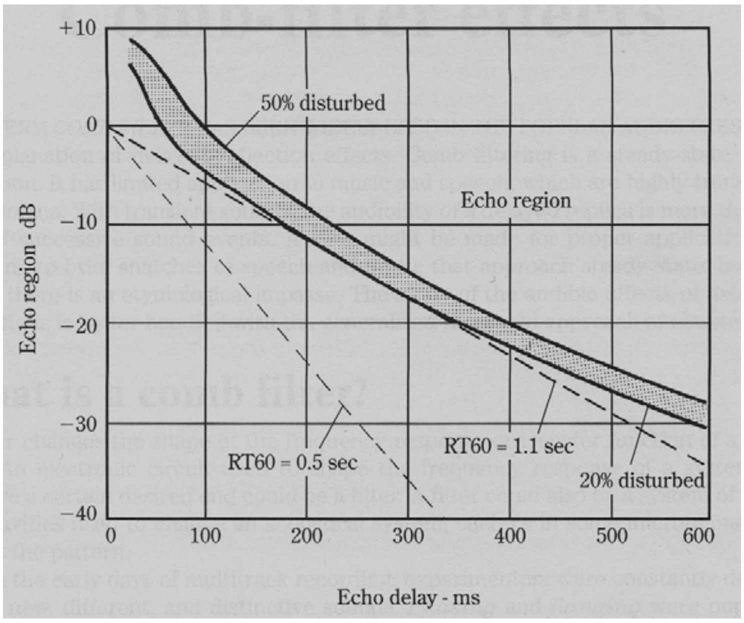


Figure 6. Acceptable echo levels for speech under reverberant conditions (Everest 301).

Among measures to reduce the concentration of reflected sound are altering the geometry of the concave surface, adding an absorptive treatment to the surface or dividing the surface into smaller parts. Either absorptive or diffusing treatment of a reflecting surface can be used, or the surface can be remodeled to direct the reflection away from performers and audience. By the way, the large areas of acoustic absorbent should be avoided as they lead to a quieter sound and holes in the directional sound distribution (Cremer 88).

2.3.4.2. Sound Foci

The concentration of a sound on a spot by the concave surface makes the sound pressure rise excessively, which is called sound foci. This makes the sound distribution irregular in the room. On the other hand, it also produces particular spots at other locations where the sounds are weak and inaudible, called dead spots (Maekawa 85). Reflection from a finite surface mainly depends on the relationship between the size of the reflector and the wavelength of the sound. A convex surface disperses sound; it is a safe feature in an auditorium and is valuable in situations where reflection from a plane surface might produce undesirable effects. On the contrary, concave surfaces are particularly dangerous because as they focus sound. If the focal point of a concave surface is near performers or audience, the reflection is likely to be heard as an echo. Highly curved surfaces which are remote from audience by the way act as dispersers of sound. Figure 7. illustrates the different reflective characteristics of these convex and concave surfaces.

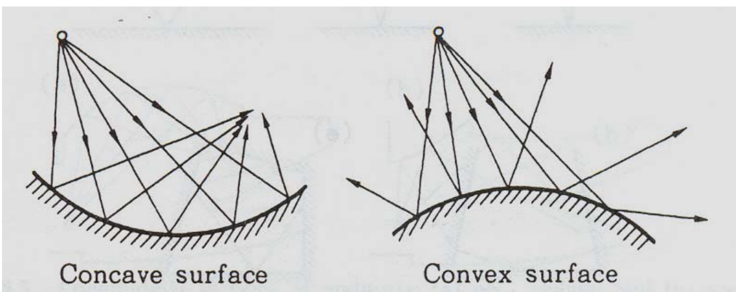
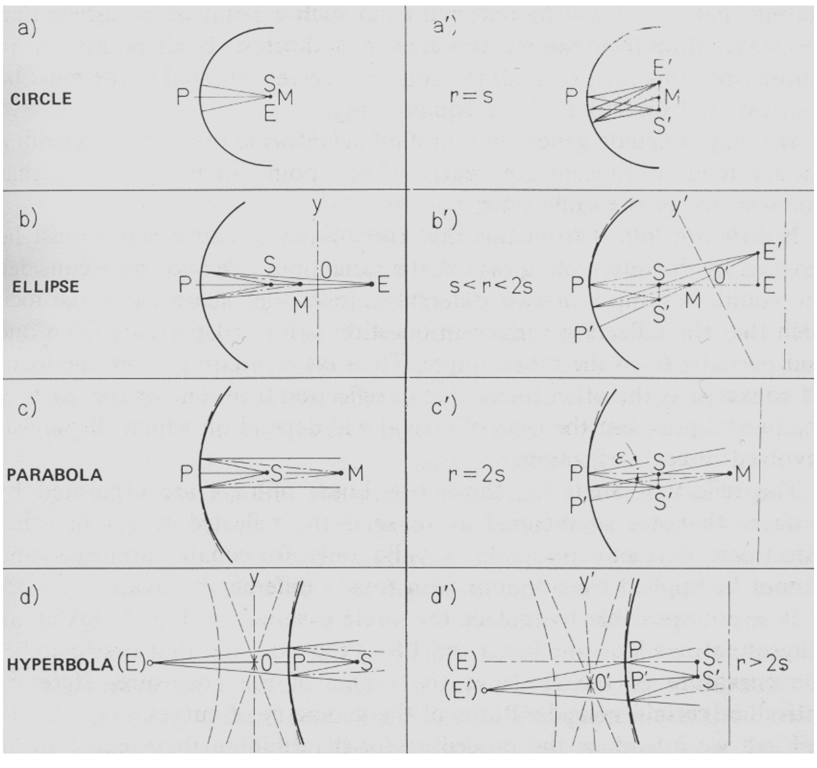


Figure 7. Reflection from a concave and a convex surface (Maekawa 247).

The acceptable reflection can be obtained from a concave surface if; neither the source nor receiver are within the extended circle of the concave surface, then the reflection should be weaker than from a plane surface. If a circular plan represents a section through a cylinder, with different time delays for different heights, the reflected sound energy concentrates along the axis. But if it is a section through a sphere, the reflected energy from the entire volume is focused at a single point which is an extreme concentration of sound energy (Cremer 45). For the estimation of the effects of concave surfaces on the room acoustics, the simple laws for rays reflected at concave mirrors that are well known in geometrical optics are generally applied. The Figure 8. is illustrating these laws that are used in the assumptions of room acoustics.



The sketches on the left pertain to a source on the axis of the curved reflector and those on the right are for a source off-axis. PS=s is the distance of the source from the reflector, PM = r is the radius of curvature of the reflector.

Figure 8. Illustrations of the concave mirror laws (Cremer 49).

Whispering galleries are a type of this focusing phenomena, which occurs especially at higher frequencies. There are different methods for elimination of all these focusing examples. The Figure 9. is illustrating three different methods for the avoidance of focusing caused by concave ceiling surfaces.

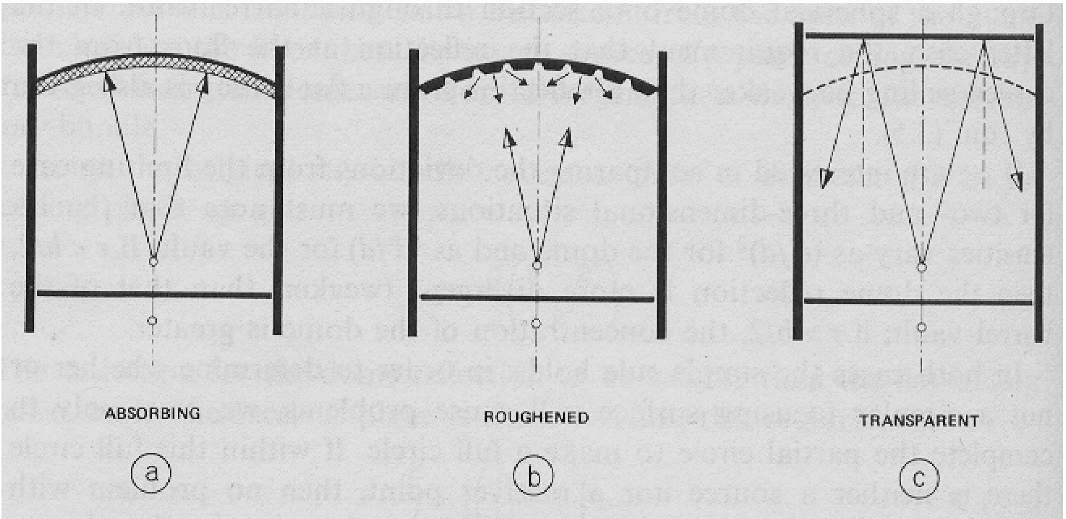


Figure 9. Methods for avoiding focusing: a)by absorption, b)by breaking up the focusing surface, c)by making the visual domed surface acoustically transparent (Cremer 62).

2.3.4.3. Sound Masking

The sound intensity of the human voice has directivity caused by diffraction by the head, much in the higher frequencies. The frequency components of consonants are tend to be in the higher frequency range and they are easily masked by the noise as the energy contents are so small although they are very critical for speech intelligibility (Cremer 30).

Vowels are consistently louder than consonants by 12 dB on average. For vowels the delay is 90 ms whereas for consonants it is 20 ms. Since vowels are both louder and of longer duration than consonants, a long room decay time causes masking of consonants, which is a common occurrence in spaces with late reflections or long reverberation time. Figure 10. is illustrating this type of a sound masking.

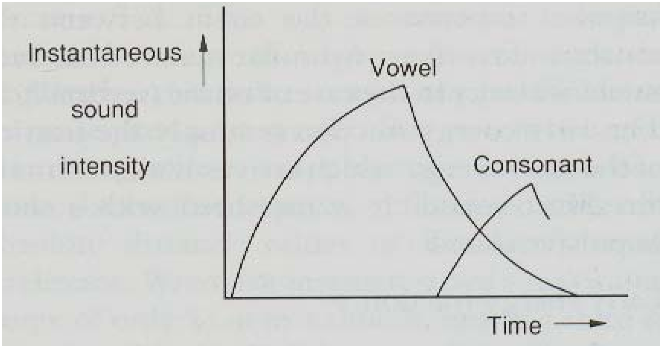


Figure 10. A partial consonant sound masking by a preceding vowel (Barron 229).

Another case is the subjective masking of the sound decay in the hall. In the design of concert halls, it is advisable to make moderate use of areas projecting the sound energy immediately towards the audience, which would result in a high fraction of early energy and in severe conditions to subjective masking of the sound (Kuttruff 263).

2.3.4.4. Coloration and Distortion of Timbre

When the time delay of reflected sound from a direct sound is short, the timbre of the sound is changed to some extent by phase interference which is called coloration. The tone of the music appears to sharpen and become more harsh for this short delays which are around 20 ms. Providing these strong early reflections invite the twin risks of that harsh of tonal quality and the false localization of source. Distortion of the initial sound signal is an undesirable acoustical defect, which could be caused by flutter echoes when the period of the sequence is less than 20 ms. In such cases, the sound signal will have a prominent coloration. Another reason for the timbral distortion is the surface finishes having a strong maximum in their sound absorption coefficient versus frequency characteristics. With a large amount of such sound absorbing material, a sharp minimum could occur in the frequency response of the reverberation time (Makrinenko 50).

Tone coloration is especially noticeable in halls with reflections from large plane surfaces; the effect is stronger for overhead reflections and constitutes one of the major reasons for avoiding suspended horizontal reflecting surfaces in concert halls. This is perceived more strongly when the sound is loud. Accordingly, the surface modulation and diffusing treatment is important for this kind of surfaces, which makes it crucial that the large unbroken plane surfaces to be avoided (Barron 187).

3. BİLKENT ODEON

The Bilkent University amphitheater with 4000 seating capacity was designed to serve the university's educational and artistic activities, and also to host the activities of the annual Ankara Art Festival in order to strengthen the dialogue with the city. The amphitheater is designed by Erkut Şahinbaş and Alpay Güleyen in 1992, in which year it received one of the design awards given within the national Architectural Awards program organized by the Chamber of Architects of Turkey, and it is inaugurated in 1999 (Türk Serbest Mimarlar Müşavirler Derneği 178).

The activities take place in the amphitheater comprise both the music and speech performances including concerts, operas, dance and stand-up shows, theaters, conferences and graduate ceremonies. At the beginning the arena was designed only for open air performances. However, afterwards it was decided to be roofed with a tensile membrane in order to protect the spectators against atmospheric effects.

Figure 11. Bilkent ODEON perspective view 1 from outside (Boyut Yayın Grubu 115).

The structure's backstage facilities house the administrative offices of the Faculty of Music together with dressing rooms and lavatories. The stage section, which rises four stories high, is partially transparent, by which it allows the audience to see the nearby setting and the view of Ankara (Şahinbaş, *Mimarlık Çalışmaları* 87).

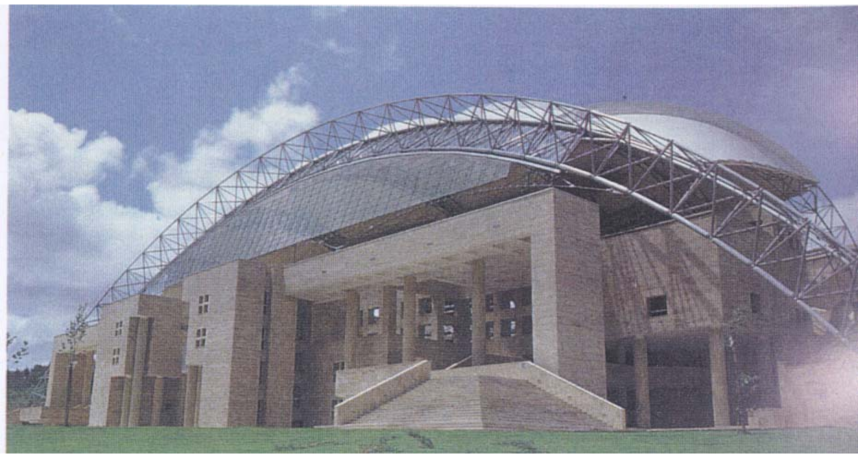


Figure 12. Bilkent ODEON perspective view 2 from outside (Şahinbaş, *Yapı* 88).

3.1. Architecture, Shape and Size

The Amphitheatre's architecture, while reminiscent of a classical Roman amphitheater, highlights the features of high technology with its steel structure roof covered by a textile membrane, besides glass and a cable network system. Consequently, the architectural form is a synthesis of two architectural styles separated by 2000 years. "Both in terms of its original form and dimensions, and the combined use of three different modern load bearing structures, Bilkent Amphitheater is the first of its kind" (Şahinbaş, *Yapı* 94).

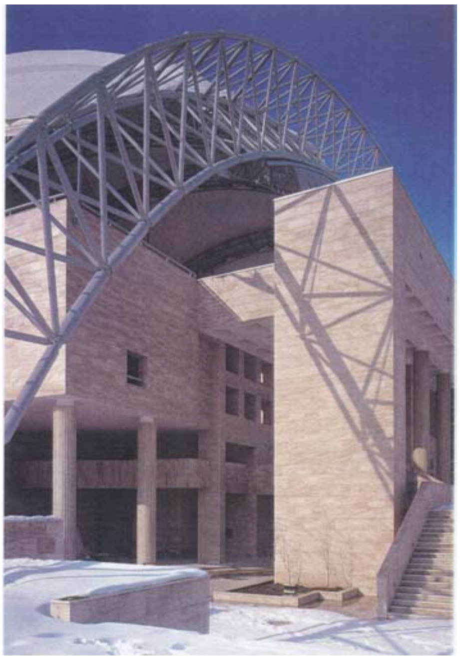


Figure 13. Bilkent ODEON the interpretation of travertine cladding with steel frame structure (Şahinbaş, Yapı 94).

Similar to those Roman theaters of the Antiquity, the Bilkent ODEON has in plan a semicircular shape. It has a radius of 48 meters corresponding nearly 100 meters in diameter and 18 meter height approximately from the stage to the top of the main arcade at the back of the seating area. The related architectural drawings of Bilkent ODEON are given in Appendix A.

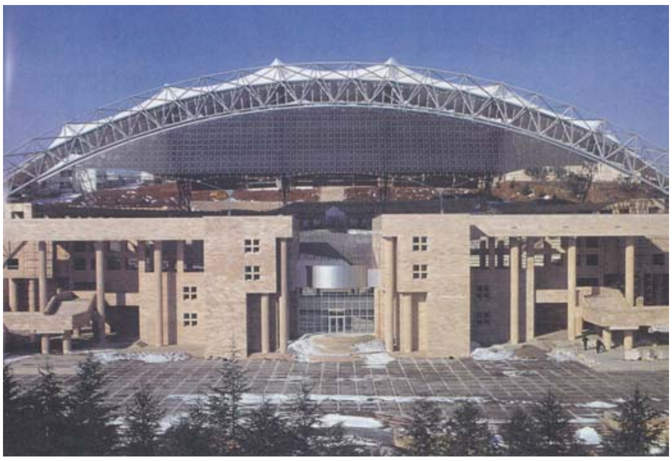


Figure 14. Bilkent ODEON front view (Şahinbaş, *Yapı* 89).

3.2. Structural and Acoustical Details

The amphitheater is built in reinforced concrete and all surfaces of the walls and staircases are cladded with travertine plates. The front and inner face of main arcade at the back of the seating area is smooth unpainted concrete. The columns of this area are also cladded with travertine which are stripped vertically. The stage is partially covered with travertine, whereas the movable part which forms the pit is wooden floor on joists. The wooden canopy over the stage has a cavity inside filled with mineral wool.

Figure 15. Bilkent ODEON interior view 1 (Şahinbaş, *Yapı* 90).

Coming to the roof structure, from two other alternatives the acceptable design is developed by a designer and manufacturer firm from Germany called MERO-Raumstruktur GmbH&Co. The system is namely a large reticulated spatial steel structure, as shallow as possible, to be covered by a membrane. What is decisive and artistic, is the request of the Architect to isolate this modern roof from the theater building with its antique Roman style. The design that is worked out by MERO matches the imaginations and ideas of the Architect to the greatest extent which is technically possible.

Figure 16. Bilkent ODEON interior view 2 (Şahinbaş, *Yapı* 91).

MERO's design consists of a steel truss system cladded with a pre-stressed membrane of PVC-coated brand polyester fabric, which is creating a half dome over the amphitheater. In front of the theater building the main steel arch truss with 118 m span ascends with 15° inclination against the vertical direction up to 35.5 m height at the vertex without touching the building at any point. The height of the key cross section is of the main arch is 49 m. This arch is loaded but also stabilized by means of six nonparallel secondary arches carrying the membrane, which have approximately 18 m intervals between their axes. Those in the centre have a height of 48 m, whereas the height of the others is approximately 42 m and 39.5 m respectively. The central secondary arches are 41 m in height at the summit which forms the highest part of the roof. All arches have triangular cross section shaped by laser welded circular steel tubes to be connected on site by means of spherical nodes.

The open area between the upper part of the main arch and of the theater building is reduced by arranging a pre-stressed rectangular cable network which are cladded with glass panels. In order to reduce deformation by wind, the steel network is linked to the reinforced concrete curtains of the proscenium by this steel cables (Şahinbaş, *Yapı* 91).

The main arch supports both its own weight, the loads created by wind and snow, and also the glass façade and the wind pressure on this façade. This load bearing system described in a simplified manner as a system of planes, is in reality three dimensional, and there is an inter-reaction between the secondary arches and the membrane roof.

The acoustical system of the hall could be mentioned basically as the canopy which is an acoustical reflector above the stage area in order to reflect sound on to the audience and back to the performers, and the acoustical grid bridges which are constructed after the building has finished and tested for its acoustics as a precaution against too much reverberance inside the hall. These acoustical grid bridges could be observed from the Figure 17.

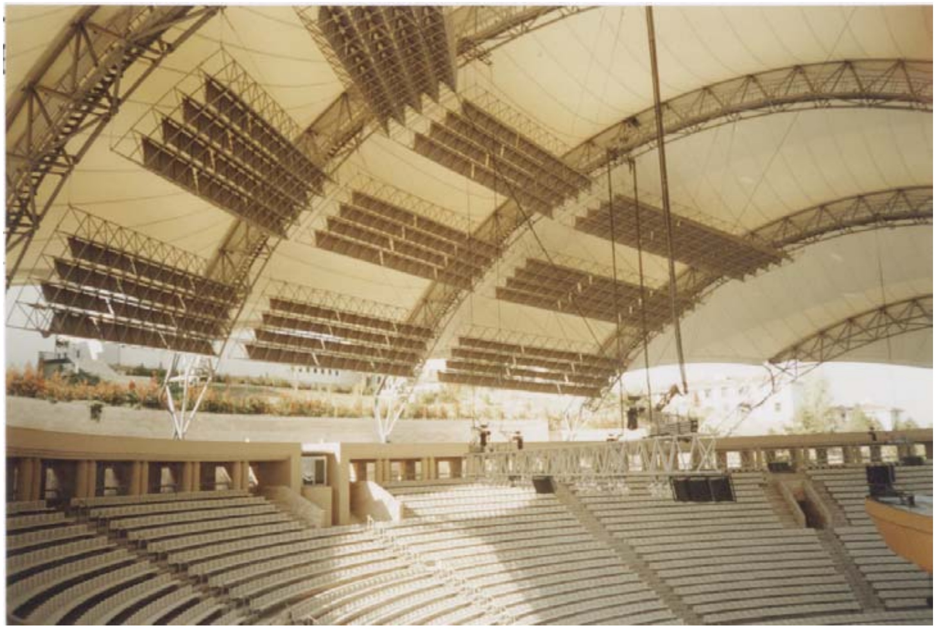


Figure 17. Bilkent ODEON acoustical bridges.

These acoustical grid bridges are composed of nine bridges that are hanged down from the secondary arches at the back part of the theater. The central three of these bridges are plane, whereas the other six are twisted giving a hypar surface. All these bridges with a span up to 18 m are double layered steel space frameworks in conventional MERO system. The members of the steel framework consist of circular, laser welded steel tubes, and are connected on site by means of spherical nodes. The structure is hot dip galvanized and has a powder coated finish. The sound absorbing acoustic fabrics, which are attached in between these acoustic bridges, are the main elements of this construction to satisfy the proper acoustical quality at the hall by absorbing the excessive sound energy especially at high frequencies.

4. REAL-SIZE MEASUREMENTS AT BİLKENT ODEON

There are mainly three theoretical approaches to the sound process in auditoriums and concert halls;

1) The statistical theory based on the assumption of an ideally diffuse sound field in the room. The basic statistical quantities used in this theory are the free path length and the mean sound absorption coefficient. With some developments in statistical acoustics, several calculation methods have been produced including Sabine, Eyring and Millington which are explained in the Chapter 2.2.1.

2) The theory of geometrical acoustics takes into account the shape of the room. This approach is the basis of both the real-size measurements and the computer simulations, which are used within the frame of this thesis. There are two methods for computer aided design based on geometrical acoustics. First one is called ray-tracing which generates many sound rays from a point source with equal solid angular spacing and traces the propagation path and reflections for each ray. The second one is called image method which calculates the positions of mirror images of a source behind reflecting surfaces, produces a drawing of sound rays by connecting the images and a receiver. Finally, from the length of the sound rays determines the impulse response at the receiver approximately (Maekawa 260).

3) The wave theory of the acoustics of auditoriums. According to this approach, the air volume of the space is considered to be a linear vibrating system with distributed parameters. The required analytical solution of the wave equation is only feasible for spaces of a very simple shape and with ideal boundary conditions (Makrinenko 3).

Real-size measurements of the hall, computer simulation and acoustic modeling are three basic evaluation methods of the halls. The statistical and the geometrical approaches are used within the calculation processes of full-size measurements and the computer simulation, which are assisted as a method of analysis under the context of this thesis. The acoustic modeling, by the way, is one of the earliest methods of evaluation the acoustic parameters and left its place to computer simulations recently which are more practical and economical (Barron 57).

4.1. Equipment, Method and Input Data

The real-size measurements of Bilkent ODEON were made by a firm namely Akukon Oy Consulting Engineers from Finland in the year 2000 in its final conditions. These measurements are important for this study, as they will provide the opportunity for comparison with computer simulation results. The overlapping status of the hall which is unoccupied for the real-size measurements are possible to be checked with the same status at the simulation software, than the other conditions for the hall which have not been evaluated in real-size measurements could be evaluated in a wider context with the simulation technique.

The parameters were calculated from the MLSSA measurement files in combination with an omni-directional sound source. MLSSA is a PC based acoustic measuring system and analyzer for the measurement and evaluation of room acoustics. It employs a maximum-length sequence (MLS) for the excitation signal as a preferred alternative to the conventional white noise stimulus. This MLS signal technique measures the impulse response, which is the most fundamental descriptor of any linear system, and from that a wide range of important acoustic indicators can be determined through computer aided post processing (Abdou 1508). The program namely WinMLS is used for obtaining the calculations in MLSSA format, which is essentially a modern windows version of it. Basically, WinMLS is a sound-card based software for high quality audio, acoustics and vibrational measurements, which is possible to be used for a large number of hardware solutions ("Information").

Measurements are commonly made with one or two source positions and at 10-12 receiver positions as a general rule (Barron 59). In this study, measurements were made for two different source locations. On the other side, eleven receiver points were determined, and for each source location these receiver points were evaluated for different parameters. In the Table 7. A. is implying the first sender or source location and B. is implying the second one. The numbers are the receiver points, which are also defined by their seat numbers and coordinates. From the side walls, the center of the backstage is considered as the origin in setting the coordinates.

Measurement Coordinates	**X**	**Y**	**Z**	**Seat**	**Measurement Coordinates**	**X**	**Y**	**Z**	**Seat**
A	-3	4	1		B	-2	5	1	
A1	31	-8	5	K93(1)	B1	31	-8	5	K93(1)
A2	34	-10	7	0105(2)	B2	34	-10	7	0105(2)
A3	39	-13	10	T111(3)	B3	39	-13	10	T111(3)
A4	46	-10	12	Y149(4)	A4	46	-10	12	Y149(4)
A5	24	-19	5	K55(5)	A5	24	-19	5	K55(5)
A6	28	-21	7	P73(6)	A6	28	-21	7	P73(6)
A7	28	-28	10	T55(7)	A7	28	-28	10	T55(7)
A8	31	-31	11	VV65(8)	A8	31	-31	11	VV65(8)
A9	18	-38	11	VV35(9)	A9	18	-38	11	VV35(9)
A10	17	-34	10	T33(10)	A10	17	-34	10	T33(10)
A11	17	-29	8	R33(11)	A11	17	-29	8	R33(11)

Table 7. Measurement coordinates for sender and receiver locations.

These positions and the perspective view points are also highlighted at the seating plan of Bilkent ODEON in the Figure 18.

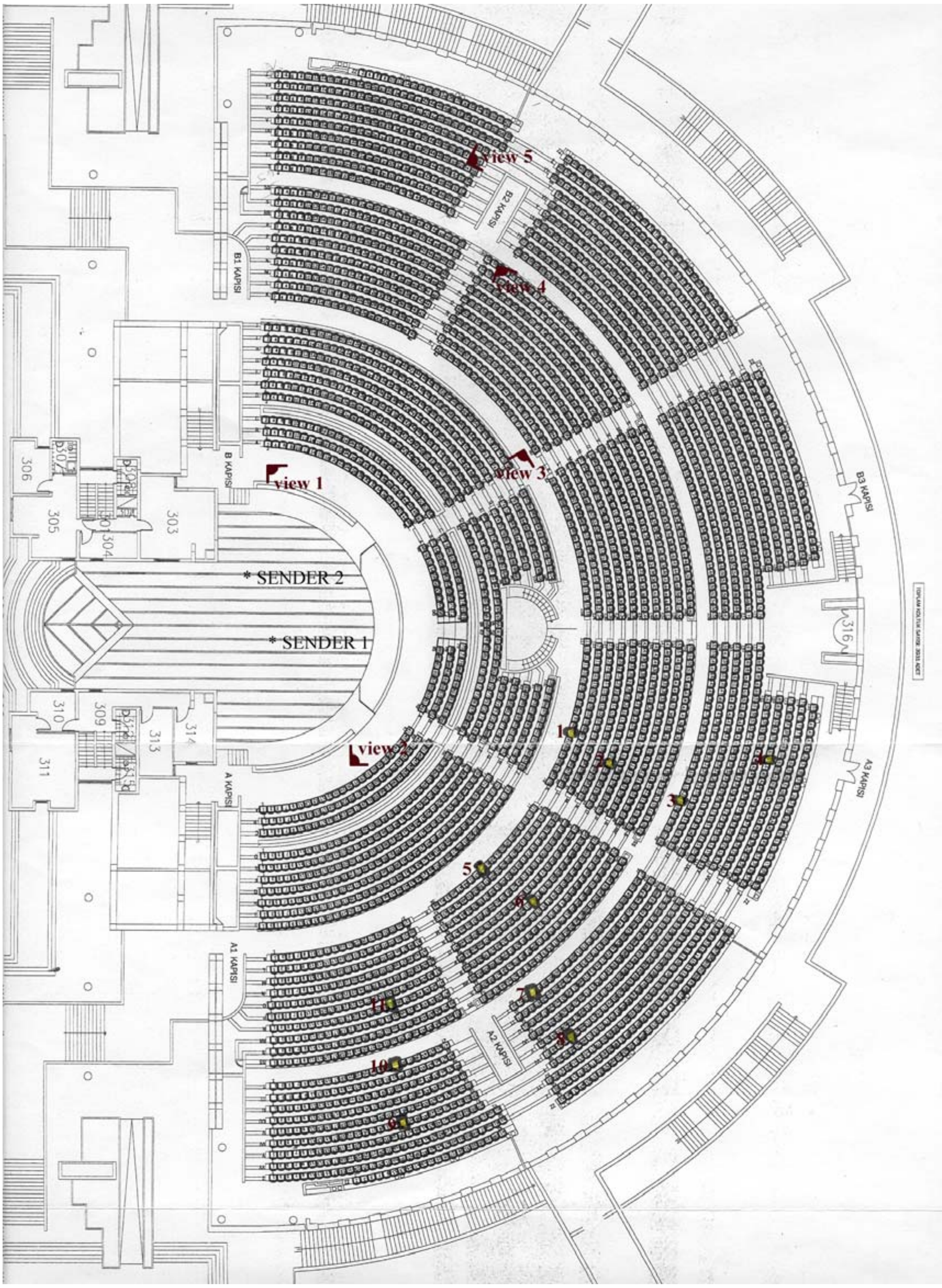


Figure 18. Selected source and receiver locations.

4.2. Measurement and Evaluation of the Results

C50, C80, D50, EDT and RT results are obtained from the impulse responses for eleven points, each for both of the two source locations. In the Table 8., Table 9., Table 10., Table 11., and Table12. the measurement results and the average values for these parameters are listed. On the other hand, much detailed graphs of impulse responses obtained from WinMLS program are given in the Appendix B.

C50 (dB)						
Receiver	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A1	-6.77	-5.8	-6.85	-8.63	-8.41	-8.34
A2	-8.20	-5.92	-8	-10	-10.4	-11.04
A3	-8.21	-6.52	-9.59	-11.75	-10.58	-10.88
A4	-7.24	-6.09	-8.72	-9.21	-10.21	-9.68
A5	-8.6	-2.45	-4.13	-7.48	-7.08	-7.55
A6	-8.19	-4.43	-6.6	-12.17	-12.19	-10.81
A7	-10.12	-3.21	-7.15	-9.77	-8.43	-7.31
A8	-9.11	-3.52	-6.54	-9.13	-8.21	-7.17
A9	-7.59	-3.1	-6.61	-12.37	-10.33	-11.19
A10	-7.81	-2.77	-6.05	-10.89	-10.38	-9.92
A11	-3.94	1.02	-5.1	-7.86	-6.5	-6.61
B1	-12.56	-7.65	-9.12	-10.89	-6.75	-5.66
B2	-10.17	-7.21	-8.59	-8.9	-7.9	-9.08
B3	-10.95	-6.06	-6.46	-8.68	-7.65	-7.37
B4	-7.94	-6.99	-10.16	-7.12	-7.22	-6.3
B5	-7.96	-6.29	-5.52	-6.81	-6.16	-6.64
B6	-11.02	-9.33	-8.01	-9.29	-9.5	-9.15
B7	-14.06	-9.44	-10.41	-12.15	-11.9	-12.37
B8	-9.79	-9.03	-8.11	-12.44	-11.03	-12.77
B9	-7.86	-4.48	-5.97	-9.04	-8.51	-7.62
B10	-7.67	-4.46	-6.24	-10.67	-8.1	-5.28
B11	-7.49	-1.28	-2.93	-7	-6.64	-4.59
Average	-8.78	-5.23	-7.13	-9.65	-8.82	-8.52
Sender	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A	-4.57	-1.21	-2.04	-5.11	-2.82	-1.8
B	-7.4	-1.47	-4.02	-7.35	-8.35	-8.42
Average	-5.98	-1.34	-3.03	-6.23	-5.58	-5.11

Table 8. Measurement results for C50 for the frequency range from 125 to 4000 Hz.

C80 (dB)						
Receiver	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A1	-5.02	-4.67	-5.8	-6.91	-6.97	-6.12
A2	-7.28	-4.65	-7.13	-8.92	-8.56	-8.6
A3	-6.9	-5.08	-7.69	-9.99	-9.44	-8.9
A4	-4.63	-3.77	-6.99	-7.2	-7.35	-7.35
A5	-6.86	-1.05	-2.67	-4.91	-5.48	-4.67
A6	-7.17	-3.03	-5.27	-8.65	-8.71	-8.31
A7	-9.11	-2.62	-5.16	-8.55	-7.05	-6.29
A8	-5.7	-2.34	-5.02	-7.56	-6.25	-5.78
A9	-3.58	-1.17	-4.7	-7.02	-5	-5.42
A10	-6.52	-2.27	-5.55	-9.81	-8.21	-6.3
A11	-3.3	1.19	-4.63	-6.8	-5.63	-4.43
B1	-8.64	-5.19	-6.63	-5.93	-4.67	-2.81
B2	-5.66	-3.76	-3.84	-5.01	-3.4	-1.82
B3	-8.46	-2.35	-3	-6.44	-5.43	-4.88
B4	-4.65	-3.29	-5.97	-3.77	-5.35	-3.48
B5	-6.99	-4.65	-4.12	-5	-3.42	-2.77
B6	-6.31	-7.38	-6.14	-5.45	-7.04	-6.02
B7	-12.54	-7.89	-8.71	-9.49	-9.47	-10.16
B8	-7.69	-6.8	-7.04	-10.06	-7.88	-9.18
B9	-6.71	-3.22	-4.82	-7.13	-6.6	-6.17
B10	-6.81	-3.59	-5.3	-8.35	-7.17	-4.18
B11	-5.12	-0.78	-2.33	-4.9	-5.25	-2.72
Average	-6.62	-3.56	-5.39	-7.18	-6.56	-5.75
Sender	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A	-3.26	-0.94	-1.61	-4.73	-2.43	-1.37
B	-6.86	-1.07	-3.79	-7.15	-8.01	-8.14
Average	-6.69	-0.99	-2.7	-5.94	-5.22	-4.75

Table 9. Measurement results for C80 for the frequency range from 125 to 4000 Hz.

D50						
Receiver	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A1	0.17	0.21	0.17	0.12	0.13	0.13
A2	0.13	0.20	0.14	0.09	0.08	0.07
A3	0.13	0.18	0.10	0.06	0.08	0.08
A4	0.16	0.20	0.12	0.11	0.09	0.10
A5	0.12	0.36	0.28	0.15	0.16	0.15
A6	0.13	0.27	0.18	0.06	0.06	0.08
A7	0.09	0.32	0.16	0.10	0.13	0.16
A8	0.11	0.31	0.18	0.11	0.13	0.16
A9	0.15	0.33	0.18	0.06	0.09	0.07
A10	0.14	0.35	0.20	0.08	0.08	0.09
A11	0.29	0.56	0.24	0.14	0.18	0.18
B1	0.05	0.15	0.11	0.08	0.17	0.21
B2	0.09	0.16	0.12	0.11	0.14	0.11
B3	0.07	0.20	0.18	0.12	0.15	0.16
B4	0.14	0.17	0.09	0.16	0.16	0.19
B5	0.14	0.19	0.22	0.17	0.20	0.18
B6	0.07	0.11	0.14	0.11	0.10	0.11
B7	0.04	0.10	0.08	0.06	0.06	0.06
B8	0.10	0.11	0.13	0.05	0.07	0.05
B9	0.14	0.26	0.20	0.11	0.12	0.15
B10	0.15	0.26	0.19	0.08	0.13	0.23
B11	0.15	0.43	0.34	0.17	0.18	0.26
Average	0.12	0.25	0.17	0.10	0.12	0.14
Sender	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A	0.26	0.43	0.39	0.24	0.34	0.40
B	0.15	0.42	0.28	0.16	0.13	0.13
Average	0.20	0.425	0.33	0.20	0.23	0.26

Table 10. Measurement results for D50 for the frequency range from 125 to 4000 Hz.

EDT (s)						
Receiver	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A1	3.76	4.55	5.08	5.18	4.49	3.84
A2	2.44	4.66	4.55	4.74	4.18	3.04
A3	3.89	5.17	5.73	5.50	4.62	3.18
A4	4.16	6.18	6.93	7.12	6.40	6.89
A5	3.43	6	6.77	7.09	6.11	5.31
A6	4.44	5.20	5.23	5.27	3.81	2.83
A7	3.54	5.17	6.09	6.41	5.71	5.03
A8	3.61	4.46	5.49	5.04	4.39	3.65
A9	4.92	5.58	6.18	6.21	5.14	4.44
A10	4.27	6.40	6.23	6.35	5.45	4.24
A11	4.46	6.14	6.21	6.49	5.81	4.68
B1	2.19	4.59	4.45	5.18	3.69	2.76
B2	2.58	3.90	5.03	4.85	4.20	2.84
B3	3.94	4.45	5.27	4.88	4.62	3.15
B4	4.26	4.94	5.95	5.80	4.96	3.59
B5	3.85	5.61	6.14	6.55	5.49	4.13
B6	3.20	4.66	5.31	5.69	4.51	2.88
B7	2.70	5.13	5.64	5.51	4.85	4.41
B8	4.04	4.94	6.26	5.58	5	3.98
B9	3.95	5.74	6.20	6.48	5.98	6.60
B10	4.43	5.83	6.34	6.65	7.68	13.99
B11	4.54	6.51	6.85	6.63	6.49	8.52
Average	3.75	5.26	5.82	5.87	5.16	4.73
Sender	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A	3.96	5.26	5.57	6.10	4.94	3.71
B	2.25	4.08	4.66	4.80	3.93	2.67
Average	3.10	4.67	5.11	5.45	4.43	3.19

Table 11. Measurement results for EDT for the frequency range from 125 to 4000 Hz.

RT (s)						
Receiver	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A1	8.71	6.10	6.39	7.22	8.82	11.58
A2	5.96	6.43	6.21	6.08	5.96	8.52
A3	8.52	5.94	6.41	6.18	5.36	5.60
A4	7.65	7.49	7.72	8.04	9.66	11.85
A5	6.02	7.67	7.42	7.91	9.17	11.21
A6	9.18	6.52	6.72	6.95	7.02	8.89
A7	9.04	8.01	8.42	8.72	10.20	11.90
A8	4.89	5.33	5.68	6.11	6.98	9.62
A9	9.92	6	5.78	6.25	7.18	9.2
A10	10.75	5.61	6.08	6.06	5.96	7.42
A11	4.66	6.08	6.43	6.52	6.93	9.05
B1	5.71	6.02	8.38	7.43	8.74	11.06
B2	4.81	5.68	6	6.45	7.59	10.76
B3	4.49	5.59	5.76	6.24	7.72	10.77
B4	5.84	5.85	5.87	6.04	6.07	7.66
B5	4.51	5.48	5.64	6.19	7.26	9.61
B6	4.45	6.46	5.92	6.06	6.36	8.65
B7	4.42	5.49	5.72	6.64	9.16	11.88
B8	5.08	6.37	6.54	6.97	8.75	11.48
B9	5.22	6.70	6.76	7.07	9.49	12.01
B10	4.93	6.18	6.66	8.41	10.88	12.53
B11	4.59	5.74	6.11	7.46	10.16	12.45
Average	6.33	6.22	6.48	6.86	7.97	10.17
Sender	**125 (Hz)**	**250 (Hz)**	**500 (Hz)**	**1000 (Hz)**	**2000 (Hz)**	**4000 (Hz)**
A	9.41	6.45	6.70	8.34	9.13	9.84
B	5.30	6.41	6.12	6.43	7.64	10.80
Average	7.35	6.43	6.41	7.38	8.38	10.32

Table 12. Measurement results for RT for the frequency range from 125 to 4000 Hz.

The average values in the tables are plotted in the graphs in order to portray the parameters apparently for different frequencies, which can be observed from the Figure 19. and Figure 20.

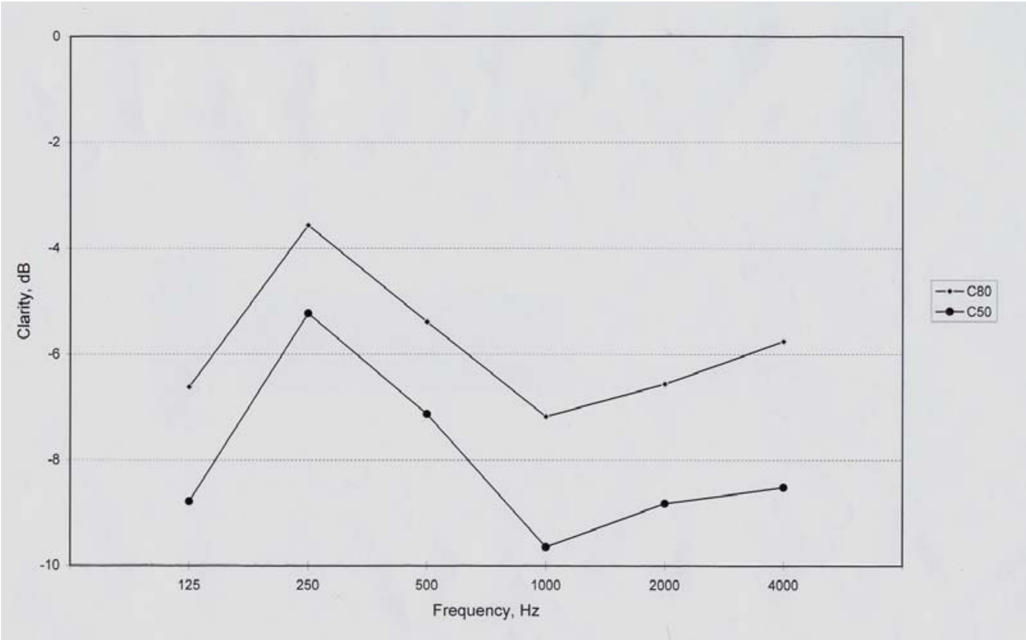


Figure 19. C50 and C80 values for frequencies from 125 to 4000 Hz.

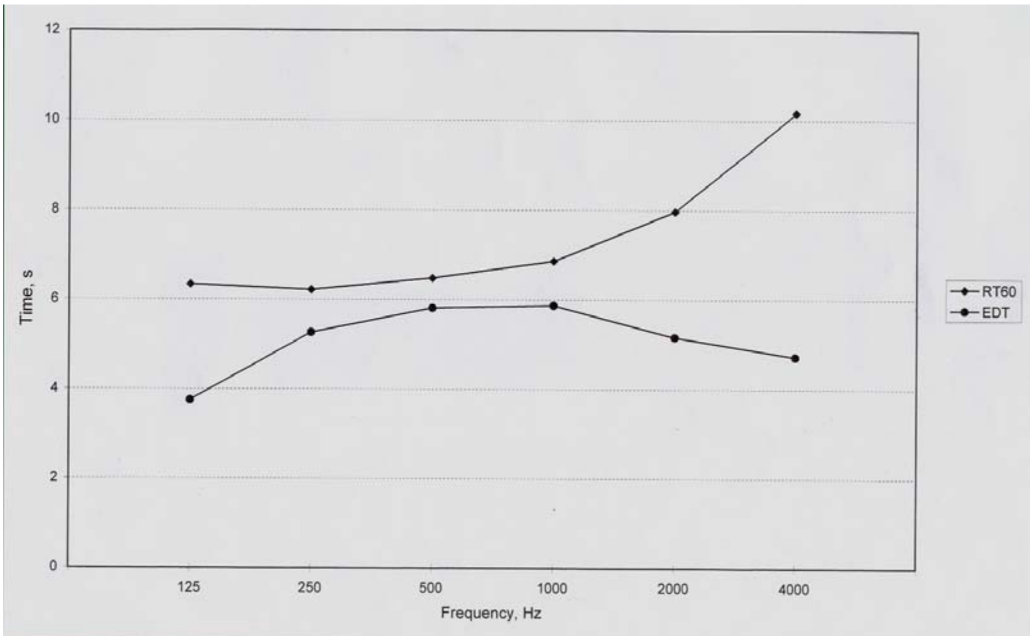


Figure 20. RT and EDT values for frequencies from 125 to 4000 Hz.

The measurements which are made when the hall is unoccupied, providing the hall to be assessed for different parameters. These parameters including C50, C80, D50, EDT and RT are listed in the tables for eleven receiver points and for two different source locations. These eleven points are chosen from different rows and tiers which could be generalized in groups as side back rows, side mid rows, back mid rows, mid center rows, mid front rows and etc. the optimum values for these parameters are given in the Table 2., Table 3., and Table 4., besides Chapter 2.2.4. and Chapter 2.3.3. The evaluations are made accordingly.

The clarity results for side back rows which are corresponding to the seats numbered VV35 and T33 are in average -5.12 dB for 500 Hz and -8.41 dB for 1000 Hz which makes an average of -6.76 dB at mid frequencies (500 and 1000 Hz) for Sender A. and an average of -6.4 dB at mid frequencies for Sender B. According to Table 2. for back rows the values lower than -5 dB are not acceptable. The seat numbered R33 could be involved into the group named mid sides, which is giving a result of -4.63 dB at 500 Hz and -6.8 dB for 1000 Hz making an average of -5.71 dB for mid frequencies for Sender A. and -3.61 dB at mid frequencies for Sender B. The value for Sender A. is just lower then the limit for the measure which is better than the mid sides but again not acceptable. On the other hand, the value for Sender B. is not acceptable but could be tolerated. The seats numbered T55 and VV65 are giving an average of -5.09 dB at 500 Hz and -8.05 dB at 1000 Hz, making an average of -6.57 dB at mid frequencies for Sender A., and an average of -8.82 dB for Sender B. These seats are in between the central back rows and the side back rows, so they could be put into the group of mid back rows. The results for mid back rows are not acceptable for clarity. Coming to the mid tiers and the mid rows, these are corresponding to the receiver point of P73 within the measurements. The average mid frequency value is -6.96 dB at this point, which is the worst value so forth for Sender A. By the way, for Sender B. the average is -5.79 dB which is also can not be tolerated. K55, on the other hand, is at the front part of the mid tiers, and the measurement result at this point is in average -3.79 dB for Sender A. and -4.56 dB for Sender B. Considering this seat location in the front rows, the value should be higher than -2 dB to be acceptable as given in the Table 2. So, this seat location is also not in the range of optimum clarity. The central part of the back tiers are signified by the seats of Y149 and T111. The measurement results for these points in average are -7.34 dB for 500 Hz and -8.59 dB for 500 Hz. This is giving an average of -7.96 dB for mid frequencies for Sender A. and -4.79 dB for Sender B. The value is lowest for Sender A. when compared to the previous ones, whereas for Sender B. the value is not good but acceptable. The central part of the mid tiers including the measurements made at the seat O105. The average mid frequency clarity result is -8.02 dB for this point which shows that these rows are even worse than central back rows for Sender A. And the average is -4.42 dB for Sender B. which is also not good but acceptable. The final measurement point could be defined as in the group of central front tiers, which is corresponding to the seating location at K93. The average mid frequency value is -6.35 dB for Sender A., which is a bit better than mid back rows, whereas worse than mid sides. For Sender B. the average is -6.28 dB, which is similar for the previous source location and not acceptable. To conclude, the clarity value appears to be best at mid sides which is closer to the limit value, while it is worst at the central part of the mid tiers among the others for Sender A. On the other hand, the results show that none of the seating points of measurements are in the acceptable range for clarity for Sender A., and only central part of the back tiers and mid tiers could be tolerated for Sender B.

The second parameter is the definition. The optimum range for the parameter is from 0.25 to 0.30 for music performance, whereas it could be fall until 0.15 for speech as specified in the Chapter 2.2.4. The definition results for side back rows which are corresponding to the seats numbers VV35 and T33 are 0.19 for 500 Hz and 0.07 for 1000 Hz in average. The average for mid frequencies are giving a value of 0.13 for Sender A. and 0.14 for Sender B, which are below the optimum range for music whereas could be tolerated for speech. The seat numbered R33, which is involved into the group named mid sides, is giving an average value of 0.19 at mid frequencies and this is also below the optimum range for definition of music. On the other hand, for Sender B. the value is 0.25 which is the limit for acceptability. The seats numbered T55 and VV65 are falling into the group of mid back rows with an average definition value of 0.17 at 500 Hz and 0.10 at 1000 Hz, which are corresponding to an average of 0.13 at mid frequencies for Sender A. and 0.08 for Sender B. The value here is unacceptable both for music and speech purposes. Coming to the mid of mid rows with the seat numbered P73, the definition value is in average 0.12 at mid frequencies both for Sender A. and B. Lower than the previous average, the mid of mid rows are not good considering the definition criteria. The next measurement point is K55 which is at the front part of the mid tiers. The average value for mid frequencies at this seating location is 0.21 for Sender A. and 0.20 for Sender B. Being better than the previous rows, the front of the mid tiers are still out of range for music. The central part of the back tiers comprising the seats of Y149 and T111 are giving an average of 0.11 at 500 Hz and 0.08 at 1000 Hz. The average mid frequency value is 0.09 for central back tiers for Sender A. Being the lowest value so forth, these rows are not acceptable considering the definition criteria. For Sender B. the average mid frequency definition is 0.13 which is also not in the optimum range. Another measurement made at the central part of the mid tiers specifically the seat O105, is giving an average value of 0.11 at mid frequencies both for Sender A. and B. As this value is lower than 0.15, it can not be accepted. The final measurement location from the group of central front tiers is the seat numbered K93. The average value for mid frequencies is 0.14 at this point for Sender A. and 0.10 for Sender B, which are also not acceptable for the definition criteria like the previous seating locations. In conclusion, besides the definition not to be evaluated as good at most of the points of measurements, among them the best area is front part of the mid tiers while the worst is central back tiers for Sender A. On the other hand the best area for Sender B. is mid sides, whereas worst is back mid rows.

The next parameter to be evaluated is EDT. For multi-purpose use the RT is accepted to be in the range of 1.4 to 1.9 s as mentioned in the Chapter 2.3.3. On the other hand, The EDT should not differ from RT more than 10%. This makes the optimum range for EDT in between 1.3 to 2.1 s for multi-purpose use as in the case of ODEON. Coming to the seats the EDT for side back rows which are corresponding to the seats numbers VV35 and T33 in average 6.24 s for mid frequencies for Sender A. and 6.41 s for Sender B. at mid frequencies. Considering the hall is unoccupied these values are still much higher than the optimum values with a top limit of 1.9 s. The seat numbered R33 corresponding to the group named mid sides has an average value of 6.35 s for Sender A. and 6.74 s for Sender B. at mid frequencies, which are out of the range. The seats numbered T55 and VV65 are falling into the group of mid back rows and have an average of 5.75 s for Sender A. and 5.74 s for Sender B at mid frequencies. The mid of mid rows with the seat numbered P73 have an average value of 5.25 s for Sender A. and 5.5 s for Sender B. at mid frequencies. K55 which is at the front part of the mid tiers, on the other hand, has an average EDT value at mid frequencies of 6.93 s for Sender A. and 6.35 s for Sender B. The central part of the back tiers including the seats of Y149 and T111 have an average value of 6.32 s for Sender A. and 5.47 s for Sender B. at mid frequencies. Next measurement point is central part of the mid tiers exemplified by the seat O105, have an average value of 4.64 s for Sender A. and 4.94 s for Sender B. Finally, central front tiers with the seat numbered K93 have an average value of 5.13 s for Sender A. and 4.81 s for Sender A. To summarize the values of EDT at the measurement points are ranging from 4.64 to 6.93 s in average at mid frequencies, none of which are in the optimum range for multipurpose use considering the hall is unoccupied.

The final parameter is RT, for which the optimum range is from 1.4 to 1.9 s for multipurpose halls, and the even distribution has a crucial importance. The average value for side back rows which are corresponding to the seats numbers VV35 and T33 are 6.04 s for Sender A. and 7.22 s for Sender B. at mid frequencies. The seat numbered R33 corresponding to the group named mid sides, have an average of 6.47 s for Sender A. and 6.78 s for Sender B at mid frequencies. Mid back rows of T55 and VV65, by the way, have an average of 7.23 s for Sender A. and 6.46 s for Sender B. at mid frequencies. The mid of mid rows with the seat numbered P73 at mid frequencies have an average of 6.83 s for Sender A. and 5.99 s for Sender B. K55 which is at the front part of the mid tiers, has an average EDT value of 7.66 s for

Sender A and 5.91 s for Sender B. The central part of the back tiers comprising the seats of Y149 and T111 have an average value of 7.08 s for Sender A. and 5.97 s for Sender B. at mid frequencies. Another measurement point at the mid tiers including the seat O105, have an average value of 6.14 s for Sender A. and 6.22 for Sender B. at mid frequencies. The final point from central front tiers is the seat numbered K93, which has an average value of 6.8 s for Sender A. and 7.9 s for Sender B. at mid frequencies. In summary, the average values for RT are ranging from 5.91 to 7.90 s. These are again much higher than the optimum RT range for multipurpose halls. Looking at the Table 12. for each seat, for both source locations and for all frequencies, it could be observed that there are a variety of values which are too different from one another with a minimum of 4.42 s to a maximum of 12.52 s. The jumps at the RT results around 10 s are seemingly caused by the acoustical defects including echoes and sound focuses at the hall mostly at higher frequencies and even at the lower ones. So, the measurement results for RT are implying an unacceptable RT throughout the hall with an uneven distribution of the sound.

When the Figure 20. is analyzed, it is found that the EDT values are lower than the RT ones. While the mid frequency values are much closer to each other, it is obviously seen that at lower and especially at higher frequencies there are big differences between the two parameters. However, it should not be higher than 10% for providing the conditions of good acoustics. The big differences of EDT from RT is implying a bad distribution of sound in the room, whereas the value to be smaller than the RT is indicating that there are surfaces which directs the early reflections on to the audience. A hall to be considered as good generally has a EDT higher than RT of 0.5 s at mid frequencies, which can not be observed in this example. The RT graph with higher values at high frequencies implies that there are surfaces which are highly reflective at high frequencies and clearly the main reason for the focuses around the hall. The different values at the EDT with an average minimum of 3.75 s and an average maximum of 5.87 s is caused by the remoteness of the surfaces in this large hall as the EDT is chiefly depends on the room geometry and distinctness of the absorptive and the reflective surfaces.

5. COMPUTER SIMULATION OF BİLKENT ODEON

The digital simulation of sound propagation in enclosures are cheaper, faster and more efficient method than the earlier method of physical models of enclosures. This technique is extremely helpful, not only for the practical design of halls of any kind but also for getting more insight into the way of geometric details of a hall, the properties of its walls, the arrangement of the audience etc. Moreover, the listening conditions at any desired position could be predicted.

The simulation program which is used in this thesis is namely ODEON Room Acoustics Program Version 5.0 and 6.1. Giving some information about the program, it should be indicated that the name ODEON which is same with the name of Bilkent amphitheater, is originally the classic, Greek Odeon evolved from the large, open-air theater into a more intimate, roofed-over venue for music performance. It is also the first known instance of the construction of concert halls. In accordance with its name, the ODEON software is basically developed for the prediction of auditorium acoustics. It is ideal for the prediction of large-room acoustics including concert halls, opera houses, foyers, underground stations, airport terminals, industrial workrooms and various auditoria (Brüel&Kjaer 2).

The calculation method is based on prediction algorithms including image-source method and ray tracing, which allows reliable predictions in modest calculation times. Besides the geometrical approach, the statistical properties of the room's geometry and absorption are also proven to be efficient in the ODEON Room Acoustics Program (Rindel 220).

The methodology is shortly starts with importing the model of the room in DXF format. Another option for modeling is in a parametric language. After importing the model, the sources are defined. Point sources can be defined by directivity pattern, gain, equalization and delay, allowing the definition of natural sound sources besides loudspeaker systems. There are also line and surface sources to be defined. In the next step, the receivers are defined for any calculation to be carried out. After deciding the numbers, positions and orientations of both the receivers and sources, the materials are assigned. Materials could be selected from an extendable library of materials of ODEON software, whereas new materials could also be defined with absorption coefficients from 63 to 8000 Hz and with a scattering coefficient. The scattering coefficient of a surface is the ratio between reflected sound power and in non-specular directions and the total sound power. It may take values between 0 and 1, where 0 means purely specular reflection and 1 means that all reflected power is scattered according to some kind of ideal diffusivity (Rindel 221-222). Moreover, a transparency coefficient may also be used.

Finishing these steps, for ensuring the reliability of calculation results, it is essential that geometries are consistent. There are number of tools for geometry verification including checking for duplicate or overlapping surfaces, ray tracing display and 3D Color display. This 3DopenGL display shows geometry, materials and source positions with the surface-assigned colors mapped on the acoustic reflectance of the surface materials. This is useful both for checking if the materials are assigned correctly and also useful for presentation purposes (Brüel&Kjaer 4).

The calculation results are including decay curves which are Quick Estimate and Global Estimate. Quick Estimate based on statistical formulae, whereas the more precise Global Estimate based on ray tracing which takes room shape and the position of absorbing materials into account. These global-decay methods can be used for checking the overall decay time and absorption in the model. The Global Estimate corresponds to the reverberation decay arranged over an infinite number of points in the model and so represents an ideal in traditional reverberation time measurements. For each receiver point in the model, the squared impulse response is calculated and shown as a decay curve and an integrated decay curve. These results can be directly compared to those measured at the same points in the real room (Brüel&Kjaer 5). From the integrated curve a number of acoustical parameters are calculated for each receiver point and the maps of these parameters could be obtained for selected receiver surfaces. Another option of the simulation is the reflector coverage, which displays the receiver area covered by a number of reflectors for a selected source position (Brüel&Kjaer 8).

5.1 Method and the Input Data for the Simulation

The ODEON amphitheater is modeled in Autodesk Architectural Desktop 3 as a surface model made up of 3dfaces. The file is saved in dxf format and imported to the ODEON Room Acoustics Program Version 5.0. After opening the room in ODEON, the model is checked for the missing, misplaced, wrapped and overlapped surfaces. The ray-tracing display is also used in the verification of the room geometry. Another way of verification is the 3d color display, which shows the geometry and the different materials of the hall. The following figures are the views from different locations of the hall as a 3d color display.

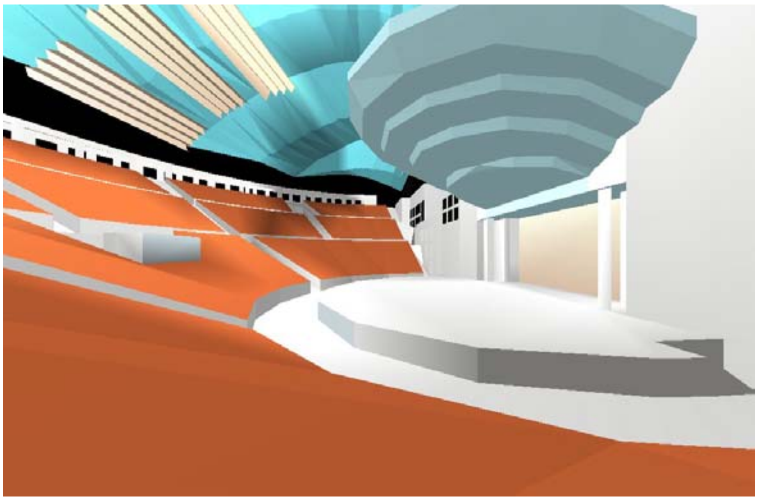


Figure 21. 3d color display of ODEON amphitheater view 1.

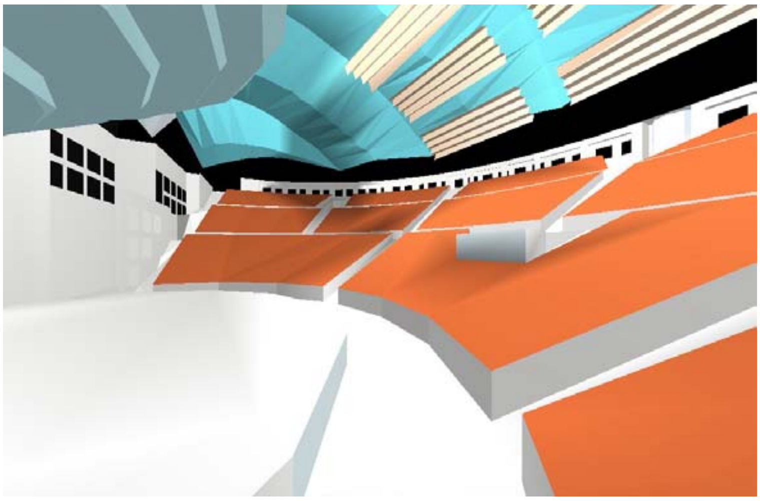


Figure 22. 3d color display of ODEON amphitheater view 2.

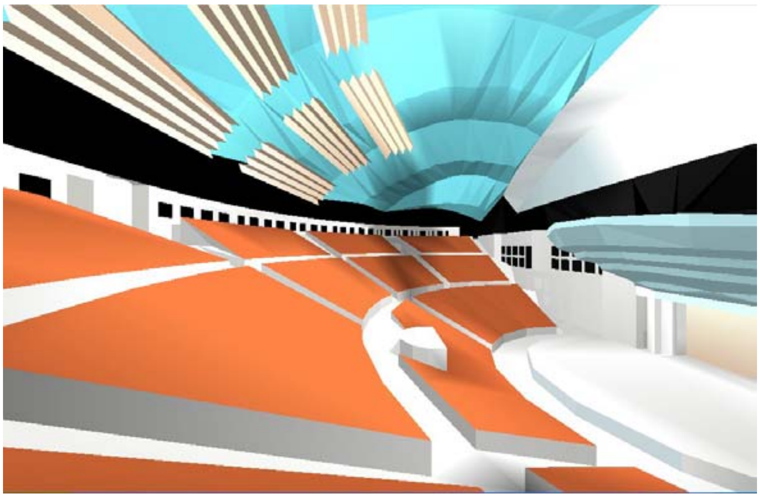


Figure 23. 3d color display of ODEON amphitheater view 3.

When the model is opened, the information of the room could be readily obtained from the software as given in the Table 13.

Quantities	
Number of corners in room	1982
Number of surfaces in room	2243
Number of verticies in room	7824
Total surface area	5865,42 m^2
Estimated room volume	89585,64 m^3
Dimensions	
Max. X - Min. X	54,45 m
Max. Y - Min. Y	93,32 m
Max. Z - Min. Z	40,25 m

Table 13. Room information for the amphitheater that is taken from the simulation software.

After the checking process is fulfilled, one source and one receiver are defined for any calculation to be carried out afterwards. An omni-directional point source is located at the given coordinates of x: -8735 m, y: -180 m, z: -34 m. The receiver is located at the given coordinates of x: -8715 m, y: -160 m, z: -26 m. Source and receiver locations are shown in the Figure 24., Figure 25. and Figure 26. The red object is implying the source, whereas the blue one is the receiver.

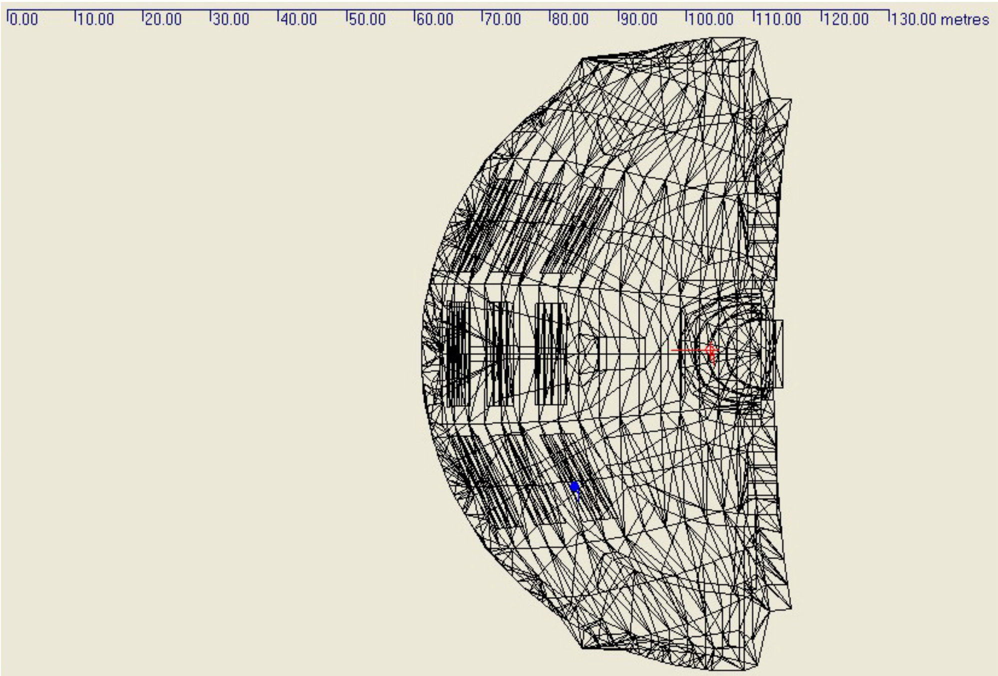


Figure 24. Plan view of the source and receiver locations.

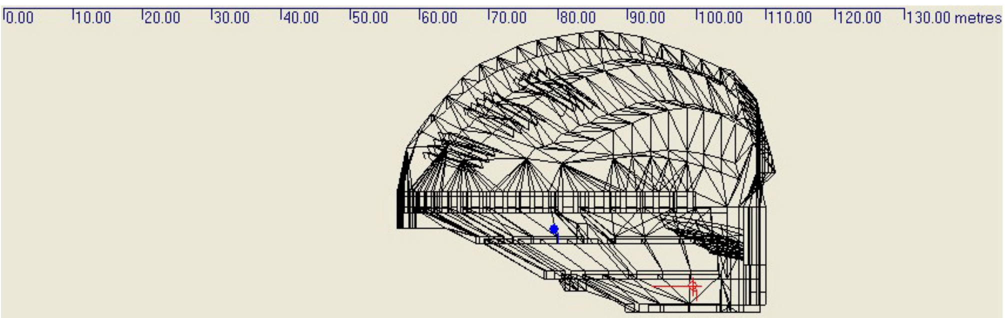


Figure 25. Elevation view of the source and receiver locations.

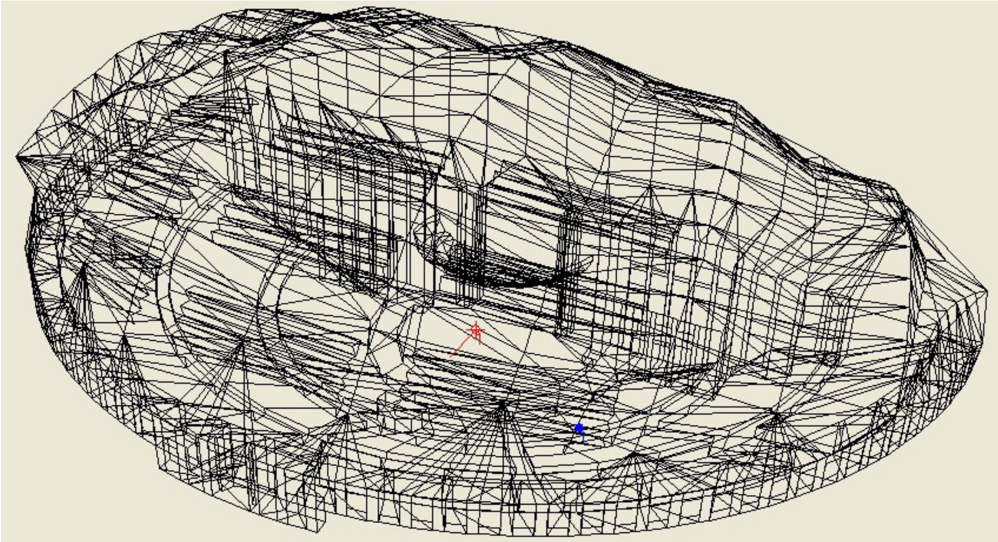


Figure 26. 3d view of the source and receiver locations.

After defining the source and the receiver, the materials are assigned for different surfaces which are layered in groups accordingly in the cad drawing. The sound absorption coefficients and the scattering factors of different materials used in ODEON amphitheater are listed in the Table 14. The material numbers are taken from the material library of ODEON Room Acoustics Program Version 5.0.

Material Number	**Material Specification**							
1	%100 Absorbent (Lynge 69).							
Scattering Factor	0,00							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Material Number	**Material Specification**							
101	Smooth unpainted concrete (Lynge 69).							
Scattering Factor	0,20							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,01	0,01	0,01	0,02	0,02	0,02	0,05	0,05

Table 14. (Cont.) →

Material Number	Material Specification						
401	Marble slabs (Approximated for the travertine floor and wall cladding) (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Material Number	**Material Specification**						
500	Wooden floor on joists (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,15	0,15	0,11	0,10	0,07	0,06	0,07	0,07
Material Number	**Material Specification**						
600	Single pane of glass (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,08	0,08	0,04	0,03	0,03	0,02	0,02	0,02
Material Number	**Material Specification**						
601	Double glazing, 2-3 mm glass, 10 mm gap (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,10	0,10	0,07	0,05	0,03	0,02	0,02	0,02
Material Number	**Material Specification**						
602	Double glazing, 2-3 mm glass, >30 mm gap (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,15	0,15	0,05	0,03	0,03	0,02	0,02	0,02
Material Number	**Material Specification**						
603	Solid wooden door (Lynge 70).						
Scattering Factor	0,20						
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,14	0,14	0,10	0,06	0,08	0,10	0,10	0,10

Table 14. (Cont.) →

Material Number	**Material Specification**							
703	Plasterboard on frame, 13 mm boards, 100 mm cavity filled with mineral wool (Lynge 71).							
Scattering Factor	0,30							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,30	0,30	0,12	0,08	0,06	0,06	0,05	0,05
Material Number	**Material Specification**							
2267	Audiences, seated audience on wooden chairs, ca. 1 pers/m² (Approximated for the shell mounted transit seat 550 mm of OMK Design, London).							
Scattering Factor	0,50							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,16	0,16	0,24	0,56	0,69	0,81	0,78	0,78
Material Number	**Material Specification**							
123457	Lightweight drapery (Egan 52).							
Scattering Factor	0,50							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,03	0,03	0,04	0,11	0,17	0,24	0,35	0,15
Material Number	**Material Specification**							
123458	Absorption fabric (Low approximation).							
Scattering Factor	0,20							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,03	0,03	0,03	0,10	0,20	0,25	0,25	0,30
Material Number	**Material Specification**							
123459	Tent fabric (PVC-coated brand polyester fabric) (Approximation).							
Scattering Factor	0,20							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,70	0,50	0,30	0,10	0,05	0,05	0,05	0,05

Table 14. (Cont.) →

Material Number	Material Specification							
123461	Chair, metal or wood seat, unoccupied (Approximated for the shell mounted transit seat 550 mm of OMK Design, London) (Abdülrahimov 131).							
Scattering Factor	0,20							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,02	0,02	0,02	0,03	0,04	0,04	0,05	0,05

Table 14. Sound absorption coefficients of different materials used in the design of ODEON amphitheater.

The simulation is made twice for different conditions of audience occupancy. In the first part (See Chapter 5.2.) the amphitheater is considered as unoccupied in order to compare the results with the real-size measurements. The material numbered 123461 is applied for the seating area in that phase. In the second part (See Chapter 5.3.) the amphitheater is regarded as fully-occupied, then the material numbered 2267 is applied for the seating area. Assigning the materials to the surfaces, the calculation parameters are defined as listed in the Table 15.

Scattering method	**Lambert**
Number of rays	100000
Max. reflection order	2000
Impulse response length	5000 ms
Impulse response resolution	9,0 ms
Transition order	2
Number of early scatter rays	50
Late reflection density	100 ms

Table 15. Calculation parameters of the model that are applied in the simulation.

After fixing the calculation parameters, the selected receiver surfaces are divided into grids of 0.90 m. The maps of calculated parameters are defined for these surfaces. Moreover, the tent membrane and the wooden diffuser over the stage are defined as the reflector coverage. For both simulations of unoccupied and occupied halls, according to the given input data, the results of quick estimation and global estimation are evaluated. The reflector coverage and the grids are calculated in order to obtain the results of different acoustical parameters and their distribution throughout the hall.

5.2. Comparison of the Computer Simulation with the Real-Size Measurements

This part is including the simulation results of the hall assumed as unoccupied, and their comparison with the results of same conditions of the real-size measurements which are made also when the hall is not in use. The calculation results are including the decay curves. First of the two global-decay curves is the quick estimation which is based on the statistical formulae. According to the quick estimation calculations the obtained results are given in the Figure 27., Figure 28. and Figure 29.

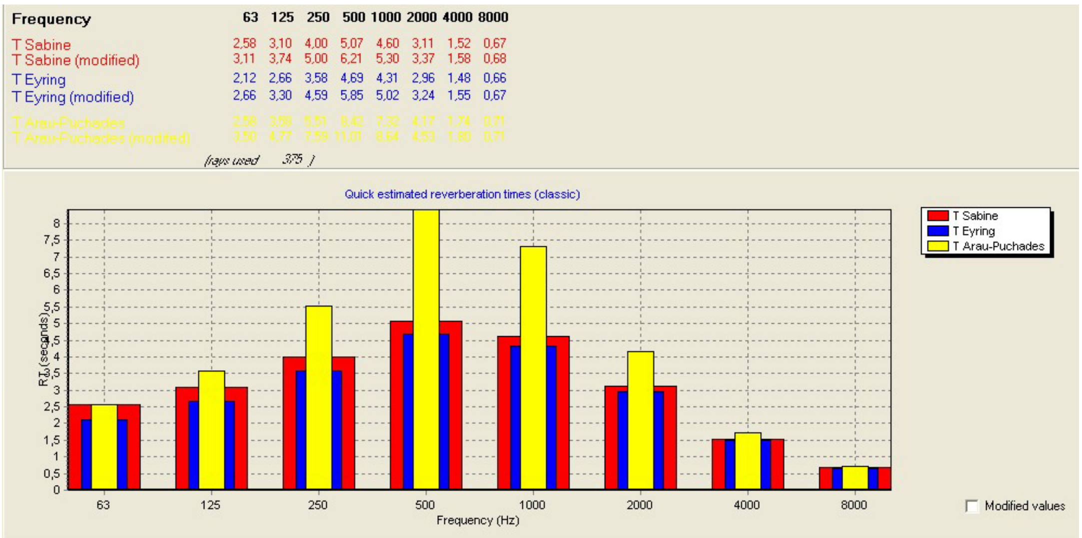


Figure 27. Estimated reverberation times of quick estimate for unoccupied hall.

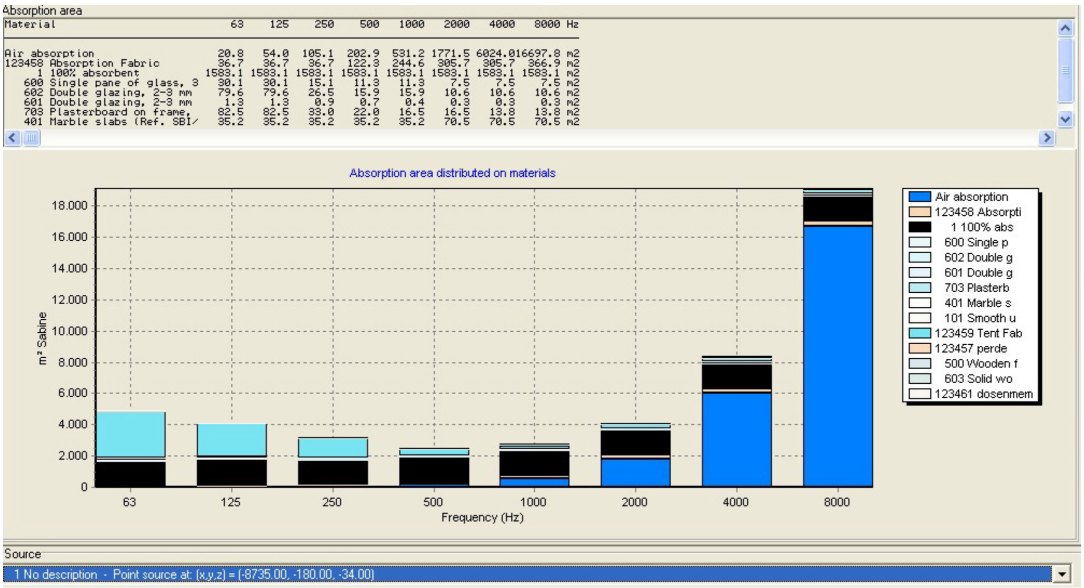


Figure 28. Material overview for unoccupied hall.

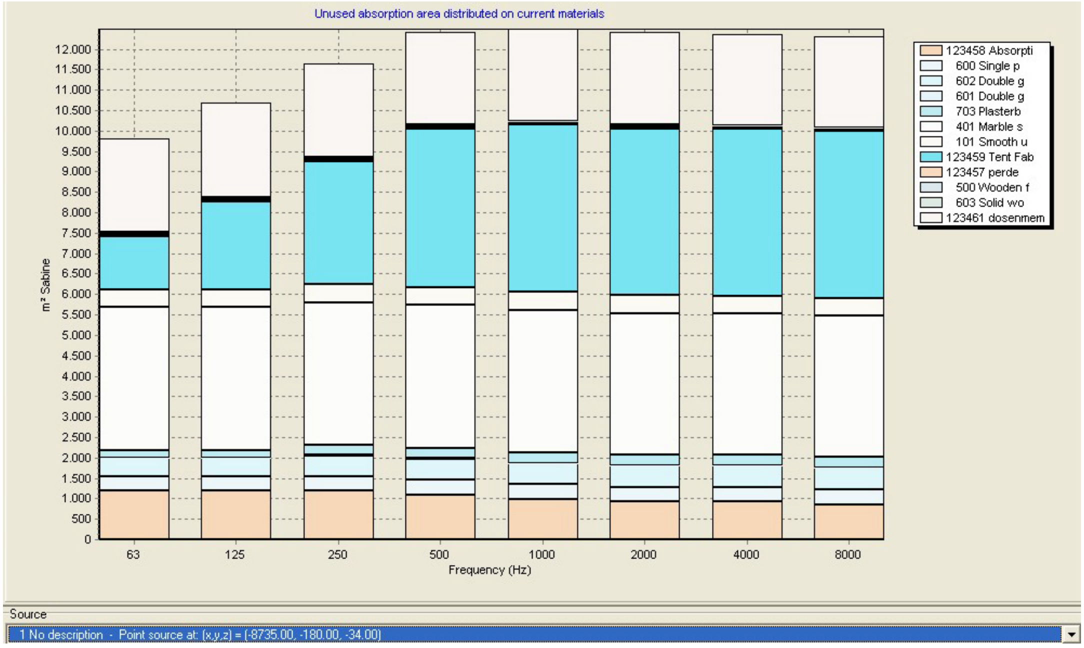


Figure 29. Unused absorption graph for unoccupied hall.

The quick estimation results show that the reverberation time for the unoccupied hall at mid frequencies (average of 500 and 1000 Hz) is 5.75 s. As this method does not take into account the positions of the materials and the room shape, the global estimate results for reverberation time is going to be taken as the basis. Considering the material overview graph, for the unoccupied hall it can be seen that for mid frequencies there is no sound absorbing material rather than the open areas around the perimeter of the membrane and the voids at the backstage from where the sound escapes. The graph also implies that the tent membrane is much absorptive at low frequencies whereas it is highly reflective at higher frequencies. As sound waves pass through the air its energy is absorbed. This is called molecular relaxation because the air molecules absorb energy when they bump each other. The major absorption effect is caused by the oxygen and water vapor in the air. The amount of absorption increases at low humidity levels. The amount of absorption is significant between 2000 and 10,000 Hz. So, the sound at high frequencies is much absorbed by air whereas at low frequencies almost no air absorption occurs as in graph of material overview. The unused absorption graph illustrates the reflective materials basically. The tent membrane of PVC-coated brand polyester fabric is covering much of the reflective area especially for the mid and high frequencies. It is followed by the travertine cladding of floors and walls which behave reflectively at all frequencies almost in equal amounts.

The second global-decay curve with a more precise calculation method is the global estimate. This is based on ray tracing, consequently it takes room shape and the position of absorbing materials into account (Brüel&Kjaer 5). The results of the global estimation calculations are given in the Figure 30., Figure 31. and Figure 32.

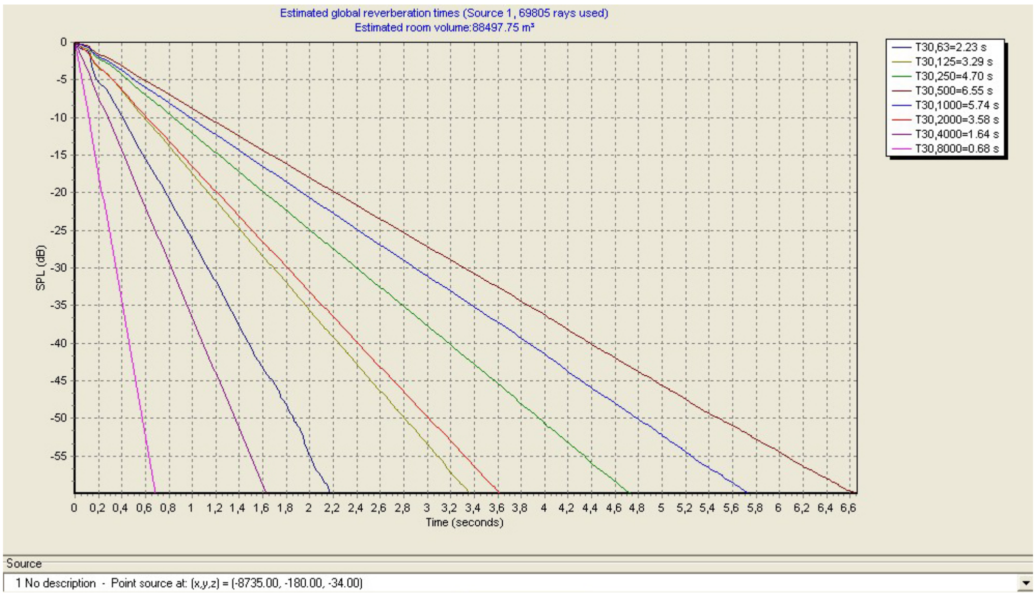


Figure 30. Energy curves for unoccupied hall.

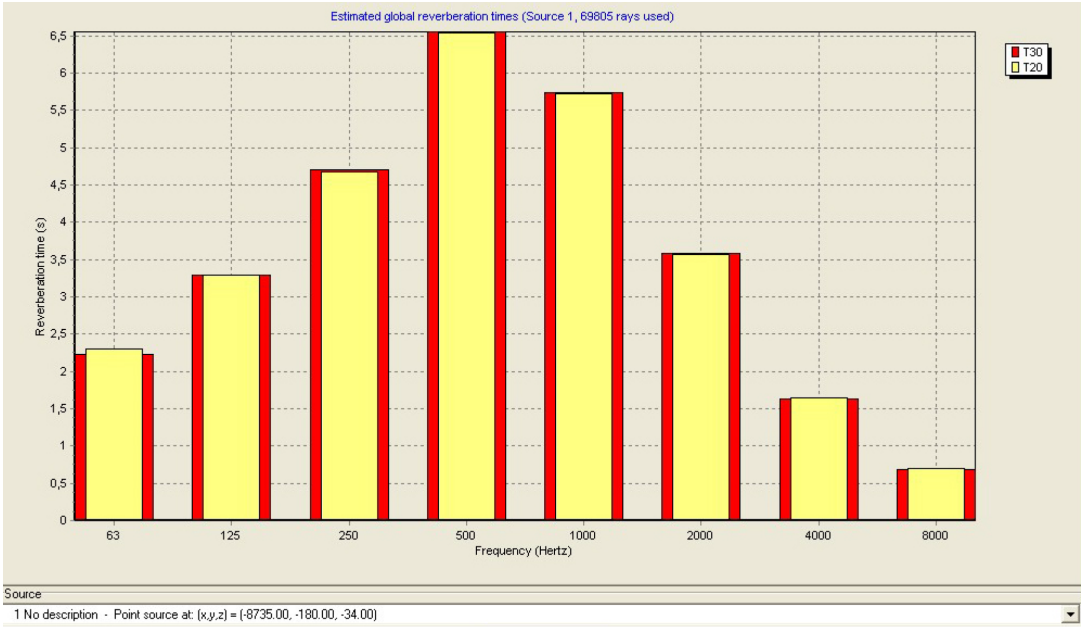


Figure 31. Estimated reverberation times of global estimate for unoccupied hall.

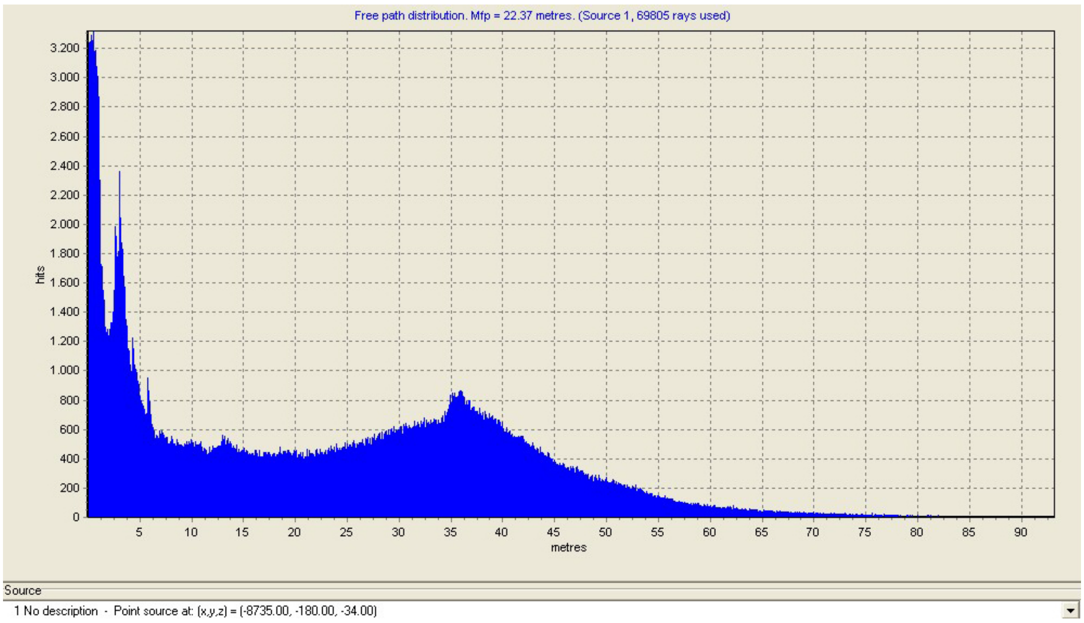


Figure 32. Free path distribution graph for unoccupied hall.

The global estimation decay curves give the result of 6.14 s at mid frequencies which is the arithmetic average of the reverberation time results of 500 and 1000 Hz. This result even for the unoccupied hall is at the much higher portions of the optimum range for music and the speech activities. The third graph of the global estimation calculations is the free path distribution graph (See Figure 32). The graph illustrates the jump within five meters, which is implying how dense the reflected sound reaches to the closer seating area and the sound wave fluctuations around that place. This is clearly caused by the symmetrical geometry of the large cut surfaces of the diffuser above the stage. On the other hand, instead of a gradually decreasing hyperbolic one, a much uneven decay curve is also caused by the very symmetrical locations and dimensions of the materials at the hall and of the overall geometry.

After taking the global estimation results, the grid responses are calculated for the selected receiver surfaces. The maps of different parameters are obtained including reverberation time (T30), early decay time (EDT), clarity (C80), definition (D50), lateral fraction (LF), sound pressure level distribution (SPL) and sound transmission index (STI). These parameters are evaluated for 500 and 1000Hz. The maps of the parameters for each of the two frequency and seven measures are listed in the following pages.

5.2.1. Reverberation Time (T30) Distribution Maps

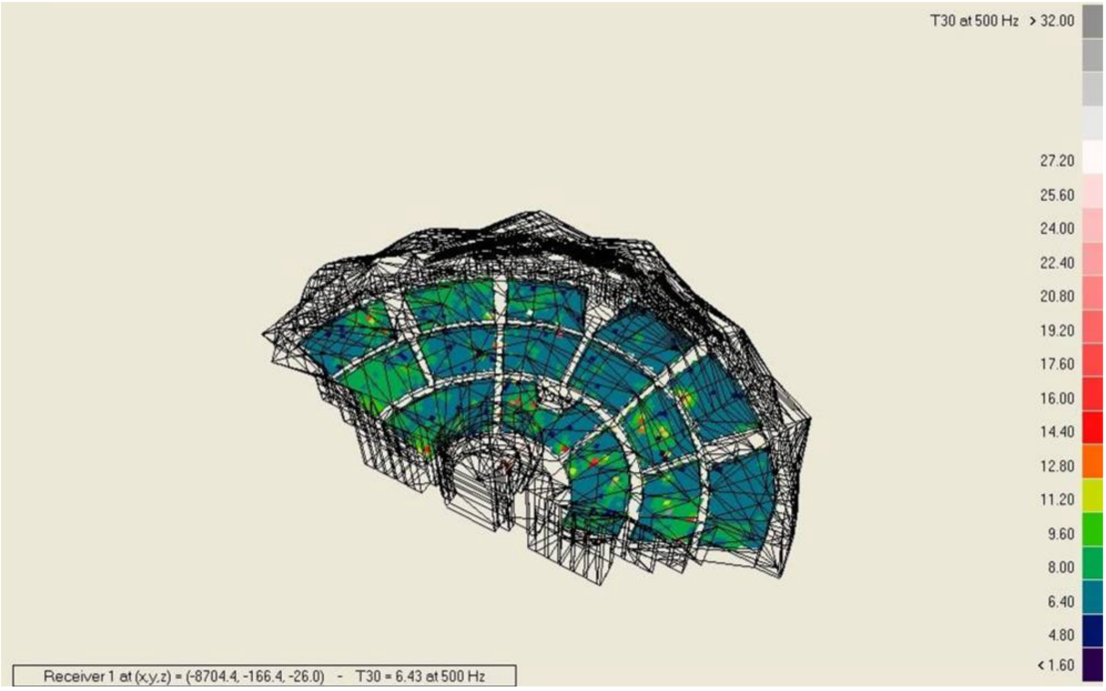


Figure 33. Reverberation time distribution map for 500 Hz and for the unoccupied hall.

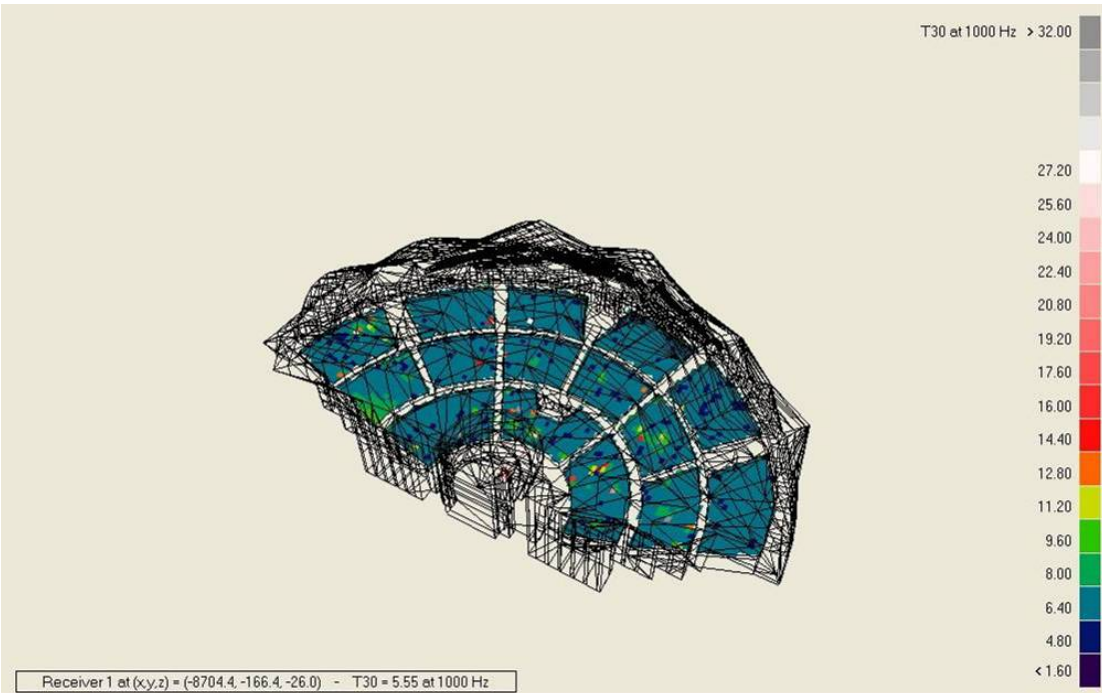


Figure 34. Reverberation time distribution map for 1000 Hz and for the unoccupied hall.

5.2.2. Early Decay Time (EDT) Distribution Maps

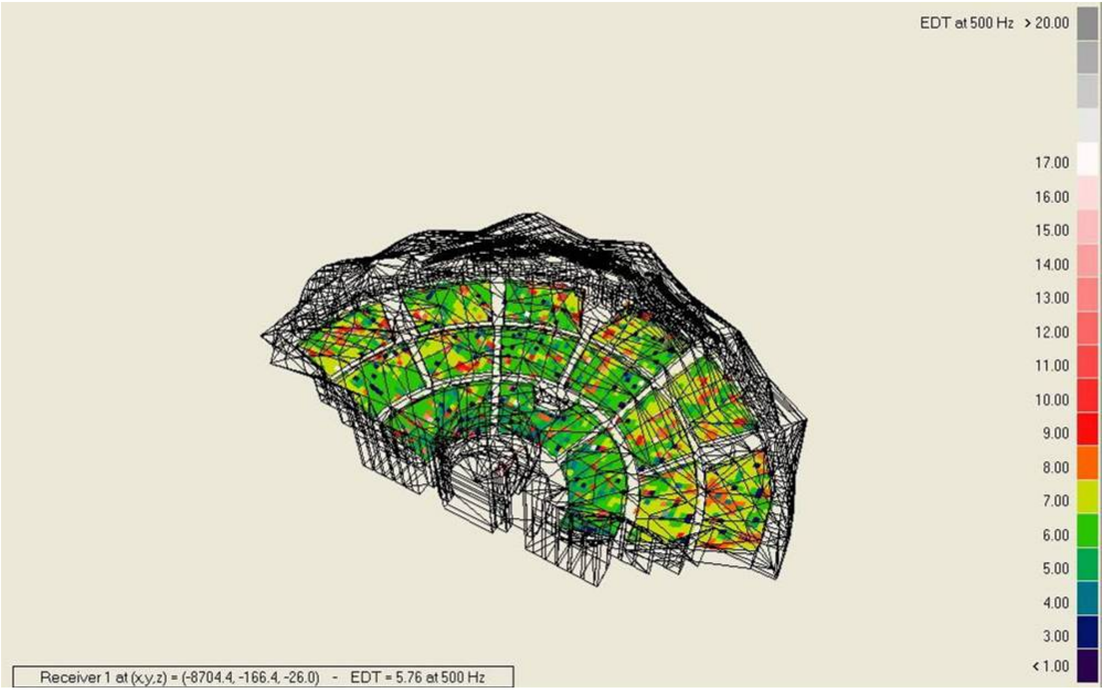


Figure 35. Early decay time distribution map for 500 Hz and for the unoccupied hall.

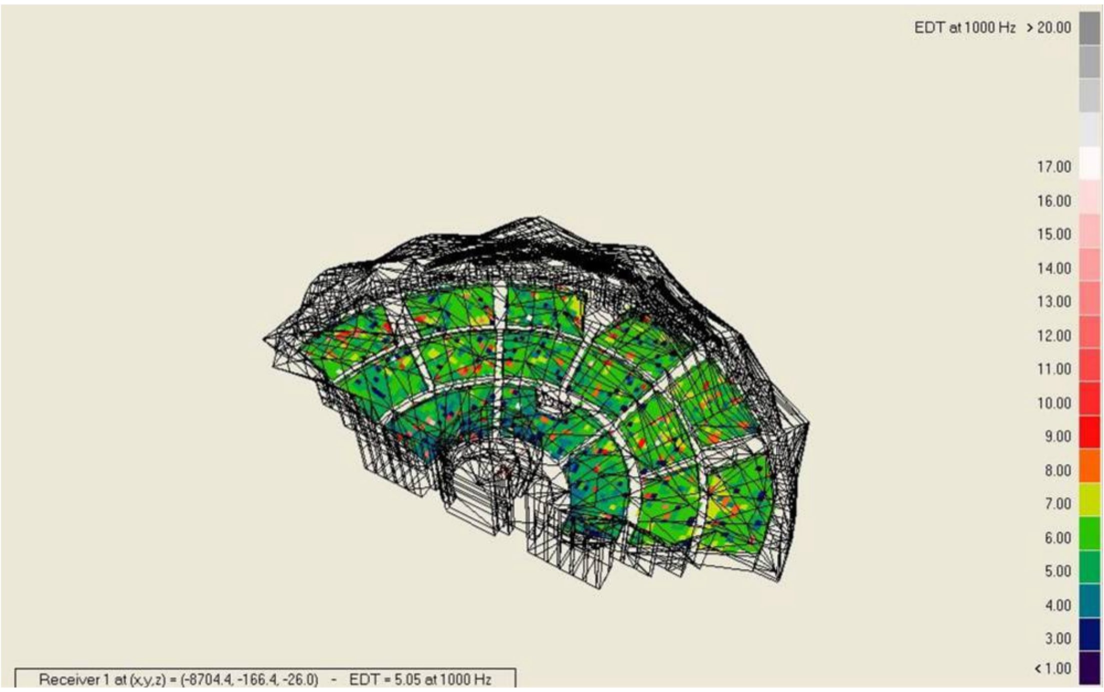


Figure 36. Early decay time distribution map for 1000 Hz and for the unoccupied hall.

5.2.3. Clarity (C80) Distribution Maps

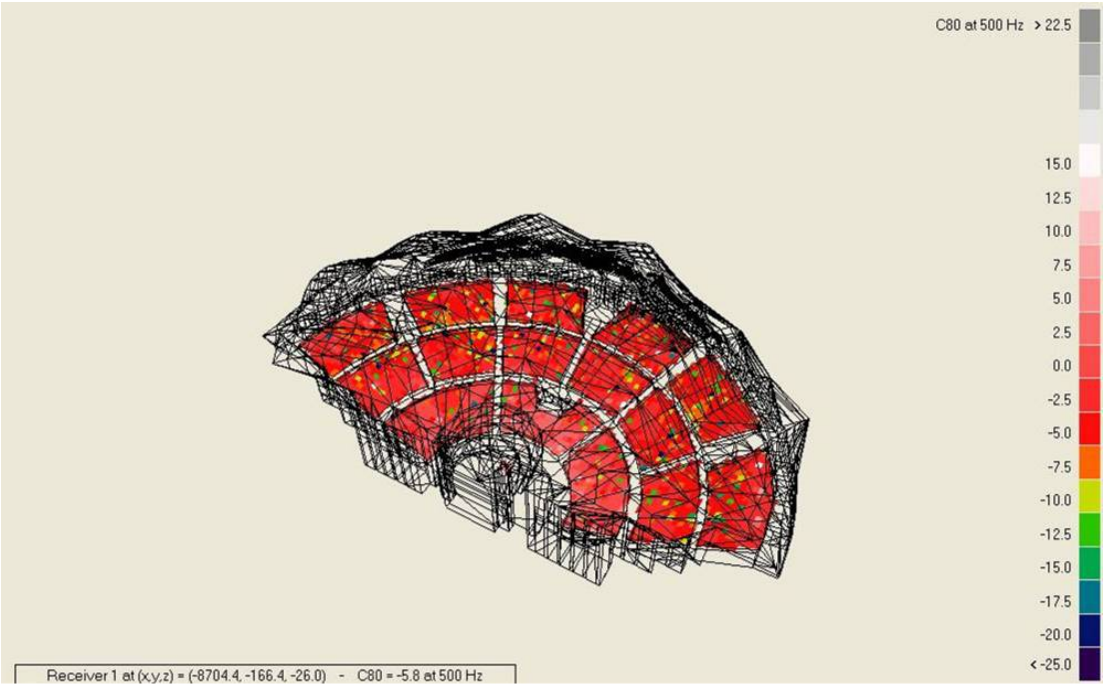


Figure 37. Clarity distribution map for 500 Hz and for the unoccupied hall.

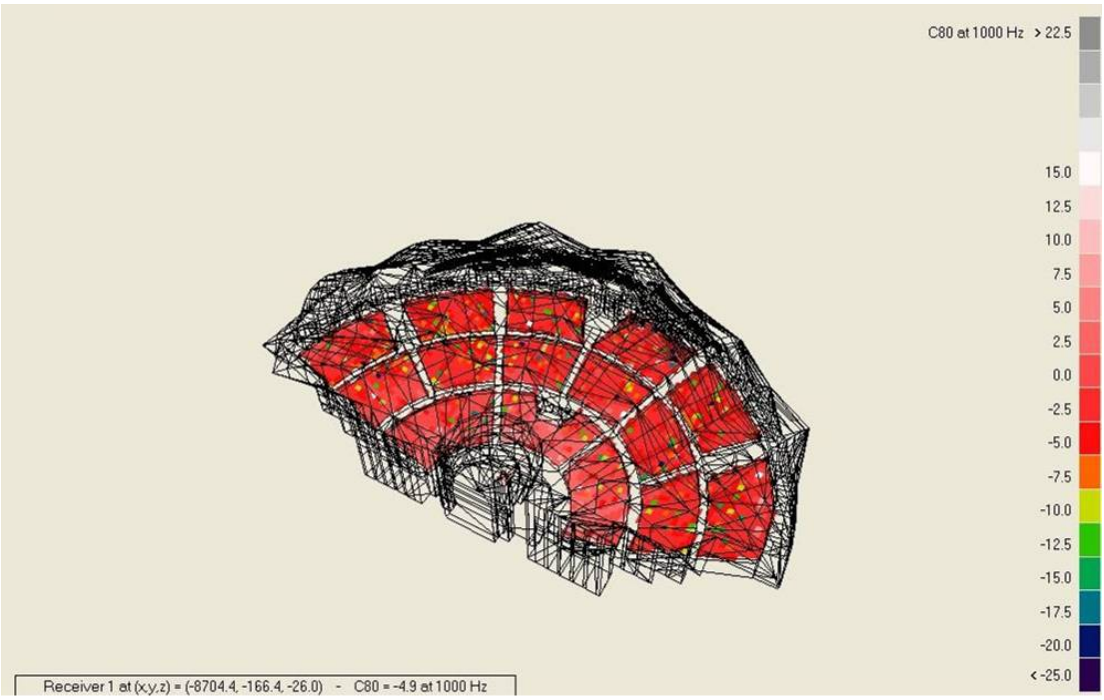


Figure 38. Clarity distribution map for 1000 Hz and for the unoccupied hall.

5.2.4. Definition (D50) Distribution Maps

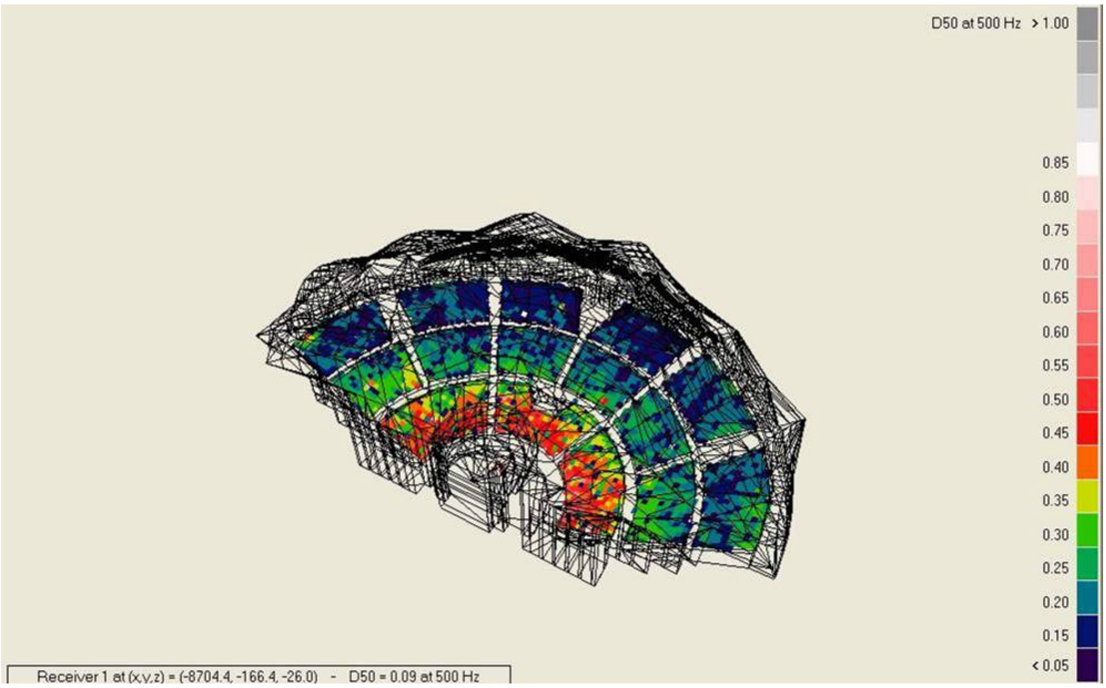


Figure 39. Definition distribution map for 500 Hz and for the unoccupied hall.

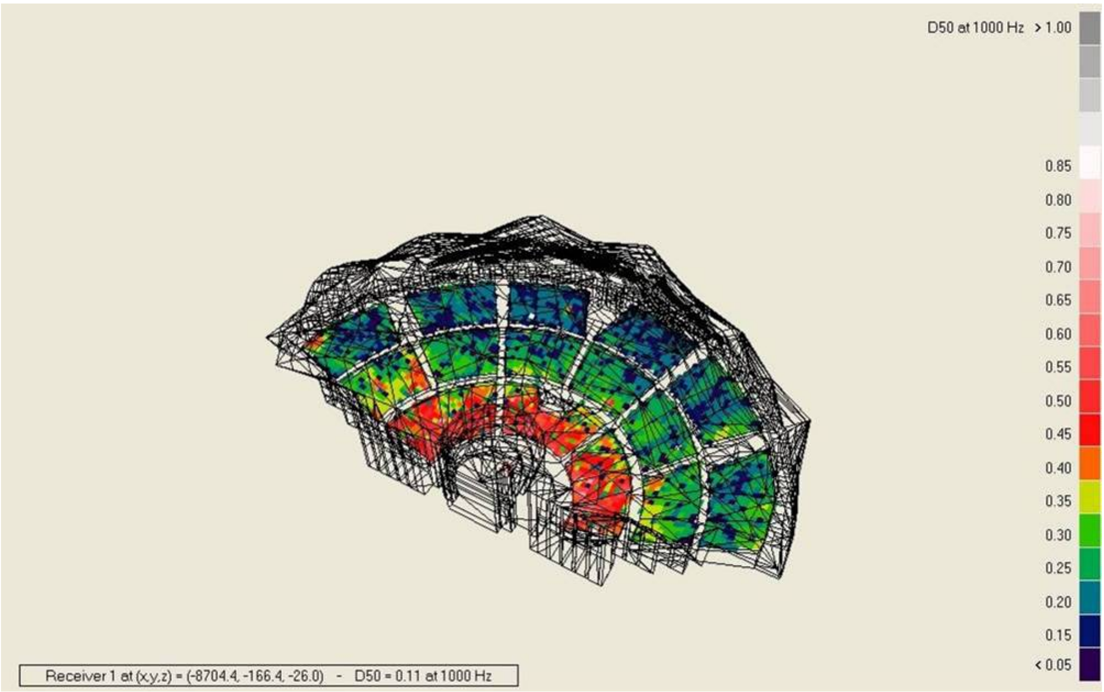


Figure 40. Definition distribution map for 1000 Hz and for the unoccupied hall.

5.2.5. Lateral Fraction (LF) Distribution Maps

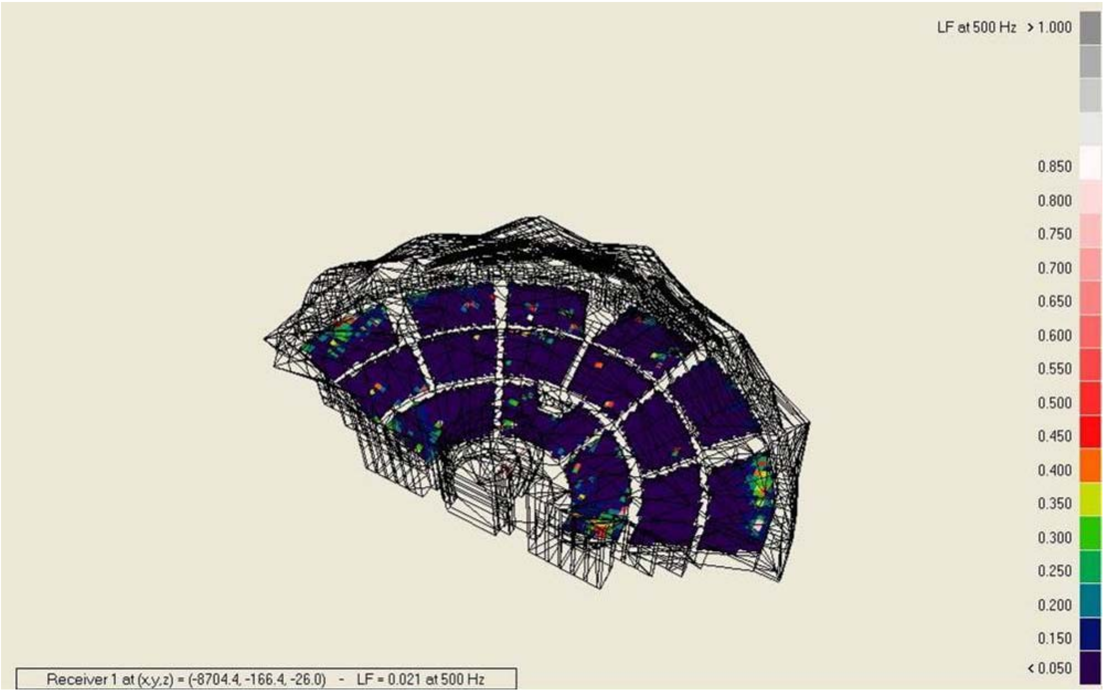


Figure 41. Lateral fraction distribution map for 500 Hz and for the unoccupied hall.

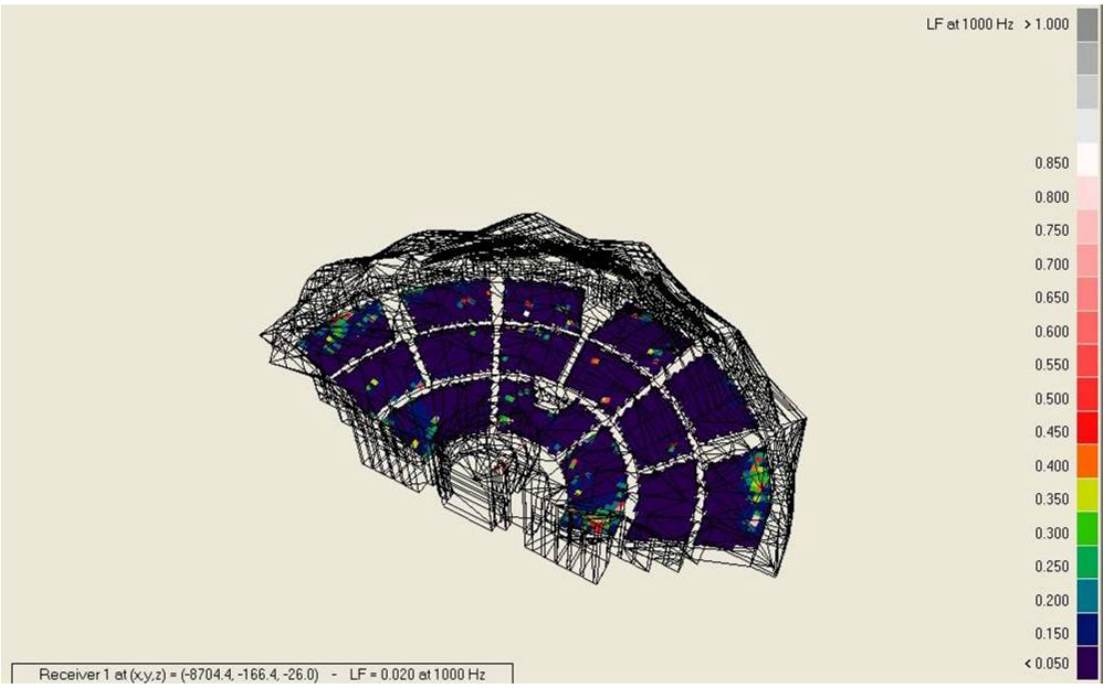


Figure 42. Lateral fraction distribution map for 1000 Hz and for the unoccupied hall.

5.2.6. Sound Pressure Level (SPL) Distribution Maps

Figure 43. Sound pressure level distribution map for 500 Hz and for the unoccupied hall.

Figure 44. Sound pressure level distribution map for 1000 Hz and for the unoccupied hall.

5.2.7. Sound Transmission Index (STI) Distribution Maps

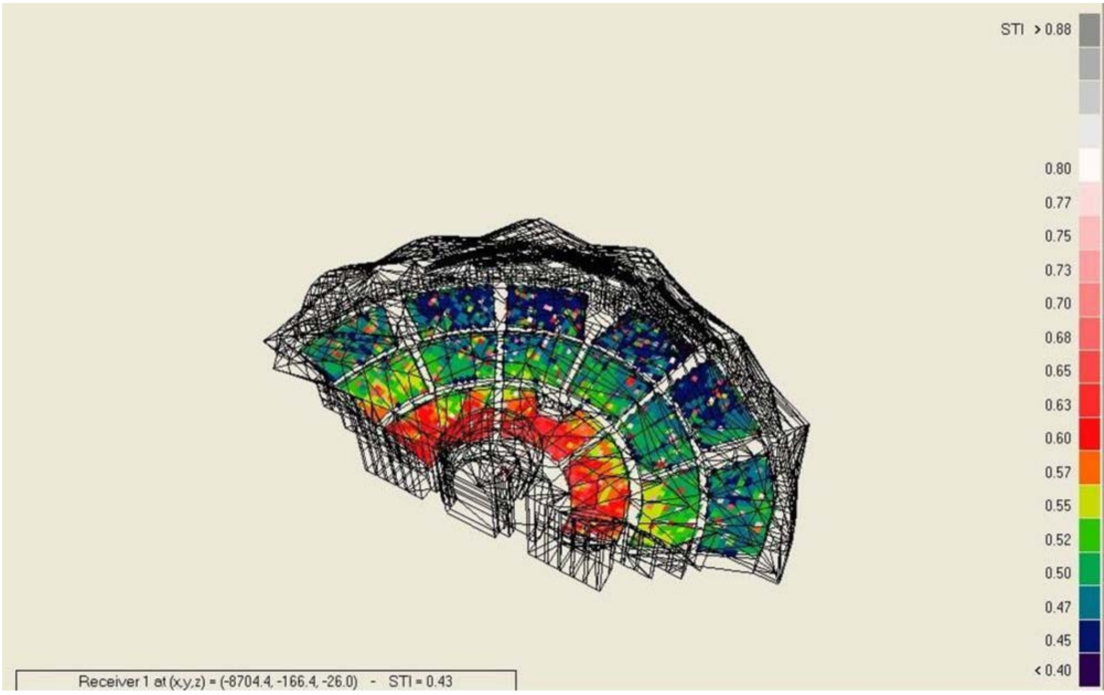


Figure 45. Sound transmission index distribution map for the unoccupied hall.

The first parameter of the grid response results is the reverberation time. The maps for 500 and 1000 Hz illustrates the distribution of the measure throughout the hall as can be observed from the Figure 33. and Figure 34. For both frequencies an uneven distribution of the parameter is apparent. The measures for different locations range in between 4.80 to 9.60 s, which is much higher than the optimum range for speech (around 1s) and for music (1.7 - 2.3 s). When compared with the overall measurements in smaller amounts there are also values ranging in between 11.20 to 14.40 s which are implying the sound focuses and echoes at this points. Although the reverberation time is a parameter which should be almost constant throughout the hall, in the maps of ODEON it could be seen that the values are changing very heterogeneously and focuses could be seen in every point including the front, back and side rows. But especially in the map of 500 Hz it is clear that the values of the reverberation time are increasing at the side seats.

The EDT values which are closer to the human sensation of the sound shows a much uneven distribution of the sound at the hall as can be seen from the Figure 35. and Figure 36. The values are in the range between 3 to 12s, with the dominance of 5 to 7s, which is also out of the optimum ranges for concert and conference halls. The overall distribution shows that the parameter has lower values at the front seats, rising at the mid and back rows while reaching the maximum at the sides. The echoes are also clear in the maps of early decay time both for 500 and 1000 Hz.

Evaluating the clarity distribution maps from the Figure 37. and Figure 38., it is seen that in the first tier involving the front seats the values are in between the -7.5 to 7.5 dB. These values, although not in every point but in some seats are corresponding to the optimum ranges of -2 to +8 dB for the front rows. However, these values are rising at the mid and back tiers, than the range this time falls in between the -5 to -12.5 dB which is unacceptable for that rows. The abrupt jumps of the values including both the rises and falls at specific points are illustrating an inefficient clarity for the overall condition of the hall.

The definition maps, as can be observed from the Figure 39. and Figure 40. show that the front tiers are ranging in between 0.55 to 0.30. Not all but some of the seats are falling into the optimum range of 0.25 to 0.30 at the front tiers for music. The front seats of the mid tiers are also in some extent providing the acceptable values changing in between 0.30 to 0.35. However, at the following back rows from mid tiers to the back tiers the values fall below 0.20 which is unwanted for the definition of the sound especially for activities related to music, and most of them are below 0.15 dB which is not good for definition of speech.

The lateral fraction which is related to the early lateral energy of the sound coming from the side vertical surfaces requires the values to be greater than 0.3 for music activities and in between 0.3 to 0.1 for other activities. Observing the Figure 41. and Figure 42., it can be seen that the overall distribution of the hall for LF illustrates the values lower than 0.05 in majority for both frequencies. The better points for the measure can be seen only at front and back sides of the hall, ranging in between 0.20 to 0.45. Like the other parameters, due to the uneven distribution of the sound throughout the hall there are also some specific points giving good values of lateral fraction other than the front and back sides.

For the sound pressure level the most important thing is the even distribution throughout the hall, so small amounts for differences at different points is required. The change of ± 10 dB is good for the sound pressure level distribution. Looking at the maps from Figure 43. and Figure 44. it can be observed that the values are ranging in between 64 to 48 dB. This shows a difference of 16 dB, which is a bit higher than the required. The higher values around 60 dB is measured in the front tiers, whereas the values are decreasing from 60 to 48 dB at the upper seats. Moreover at the back side of the hall the values fall below 46 dB, which is the lowest of the hall. There are also good measures as 64 dB at specific points of both front mid and back rows, which is implying the uneven distribution of the sound throughout the hall once more.

The sound transmission index, which is the parameter important for the speech intelligibility as can be observed from the Figure 45., is ranging in between 0.55 to 0.65 at the front tiers. This range falls into the fair to good class for the STI. At the mid tiers the values fall in to the range of 0.55 to 0.47, which is corresponding to the fair class. The side mid tiers show better results than the center of the mid tiers. Coming to the back seats, it is observed that the values are lower than the 0.47 and some lower than the 0.40 which are corresponding to the fair and bad class. Again at the back seats the sides show better properties than the mid points and they can be classified as fair.

The following evaluation is including the comparison of the real-size measurements with the simulation results in overlapping conditions in order to see the validity of the computer. These conditions are when the hall is unoccupied and the source is at the symmetry axis of the stage, which is corresponding to the Sender A. The simulation results include a wider range of parameters and measurement results presented by a variety of graphs and maps. The real measurements including four of the parameters that are also evaluated in the simulation are clarity (C80), definition (D50), early decay time (EDT) and reverberation time (RT).

In computer simulation it is observed that the clarity values for mid frequencies are ranging from -5 to -12.5 dB at the mid and back tiers. There are jumps in some points which are falling apart of this range. Looking at the real measurements, the values are in sequence, -6.76 dB at side back rows, -5.71 dB at mid sides, -6.57 dB at mid back rows, -6.96 dB at mid rows of mid tiers, -3.79 dB at front of mid tiers, -7.96 dB at central back tiers, -8.02 dB at central mid tiers and -6.35 dB at central front tiers. First of all, most of the values are in the range of the ones in simulation, and for each row and tier group the similar values could be observed from the maps of the simulation for the same locations. Much higher and lower values are also seen as jumps in some points at real measurements, as in the case of front of mid tiers. To conclude the clarity values are in consistence with the simulation and the real-size measurement results excepting a 10% deviation in much lower values.

The definition range, that is obtained from the simulation at mid and back rows, is below 0.20. Looking at the real-size measurements the values for different rows in sequence are; 0.13 at side back rows, 0.19 at mid sides, 0.13 at mid back rows, 0.12 at mid rows of mid tiers, 0.21 at front of mid tiers, 0.09 at central back tiers, 0.11 at central mid tiers and 0.14 at central front tiers. Except the front of mid tiers the values are all in the same range with the simulation. Looking at the maps of simulation in more detail it could be observed that the measurement values for different rows are consistent with the real measurements, including the front of mid tiers.

The next parameter to be compared is early decay time. The range is from 3 s to 12 s. Examining the real measurements the values for different rows are in sequence; 6.24 s at side back rows, 6.35 s at mid sides, 5.75 s at mid back rows, 5.25 s at mid rows of mid tiers, 6.93 s at front of mid tiers, 6.32 s at central back tiers, 4.64 s at central mid tiers and 5.13 s at central front tiers. All the measurements are in the range of simulation results. Looking at the maps for the values obtained from real-size measurements, it is observed that the each row is consistent with the results of simulation maps.

The final parameter is the reverberation time. Looking at the parameter for mid frequencies it is observed that the range for different seats throughout the hall is from 4.8 to 9.6 s. When the real-size measurements are observed for different row groups the measures are in sequence; 6.04 s at side back rows, 6.47 s at mid sides, 7.23 s at mid back rows, 6.83 s at mid rows of mid tiers, 7.66 s at front of mid tiers, 7.08 s at central back tiers, 6.14 s at central mid tiers and 6.8 s at central front tiers. These measurements are in the range of the simulation results. When the maps are compared with these real-size measurement results, the values are found to be consistent for each location specified in the Table 7. On the other hand, the energy curves of global estimate in simulation shows the reverberation time distribution for different frequencies. When these distribution is compared with the reverberation times of the real-size measurements for each frequency, it is observed that the results are consistent in the mid frequencies however in the high and low frequencies the result are much higher in the real-size measurements. One of the reasons for this difference is the measurement points at which focuses might occur in the real-size measurements, and make the average higher than the expected. Whereas, these focuses at high frequencies are ignored by the computer. High air absorption input data in the computer simulation for the higher frequencies, is another reason for the lower values of RT in the simulation results.

In conclusion, except the higher and lower frequencies all the measures at mid frequencies (500 and 1000 Hz) are very consistent. As the optimum values for each parameter is given at these mid frequencies the simulation program is found to be applicable in evaluations of the acoustics of Bilkent ODEON.

5.3. Simulation of the Hall for the Fully-Occupied Condition

Fully-occupied hall measurements are much closer to the real conditions of the hall in use, consequently more detailed evaluations are given under this subject. First of all, the single point response is calculated for the receiver point of the given coordinates. The results are given in the Figure 46. and Figure 47.

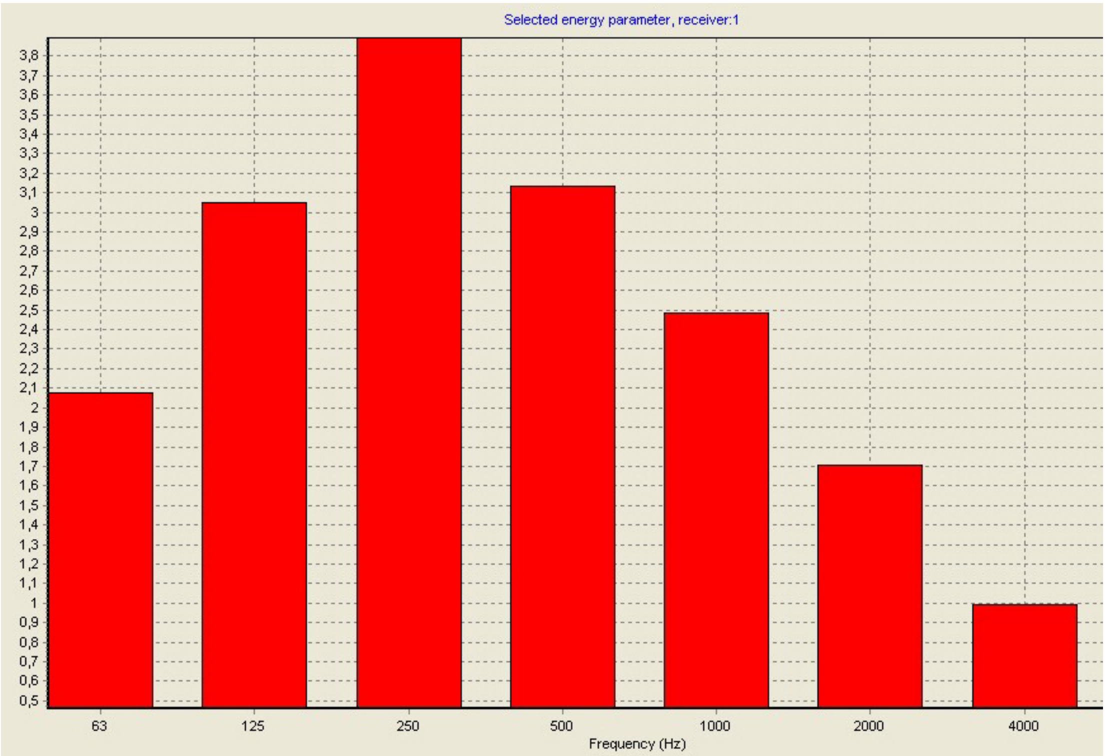


Figure 46. Reverberation times for the selected receiver point in different frequencies.

Grid receiver 1 at (x,y,z) = (-8704.4, -166.4, -26.0)

Band (Hz)		63	125	250	500	1000	2000	4000	8000
EDT	(s)	2.08	3.05	3.89	3.13	2.48	1.71	0.99	0.46
T30	(s)	1.96	2.97	3.81	3.27	2.46	1.86	1.18	0.57
SPL	(dB)	44.5	45.9	47.2	46.5	45.5	43.8	39.9	35.0
C80	(dB)	-3.0	-4.3	-4.2	-2.2	-0.9	1.1	4.0	10.4
D50		0.25	0.18	0.13	0.15	0.21	0.30	0.50	0.76
Ts	(ms)	139	209	257	211	165	112	64	23
LF		0.078	0.072	0.050	0.035	0.032	0.029	0.027	0.012

SPL(A) = 50.5(dB)
LLSPL(A) = 42.1(dB)
STI = 0.48 (Theoretical based on T30, STI = 0.45)

Figure 47. Energy parameters.

The following calculation results are the quick estimate measurements of the model. The estimated reverberation times, material overview and unused absorption graph are obtained as a result of the quick estimation calculations, which are given in Figure 48., Figure 49. and Figure 50.

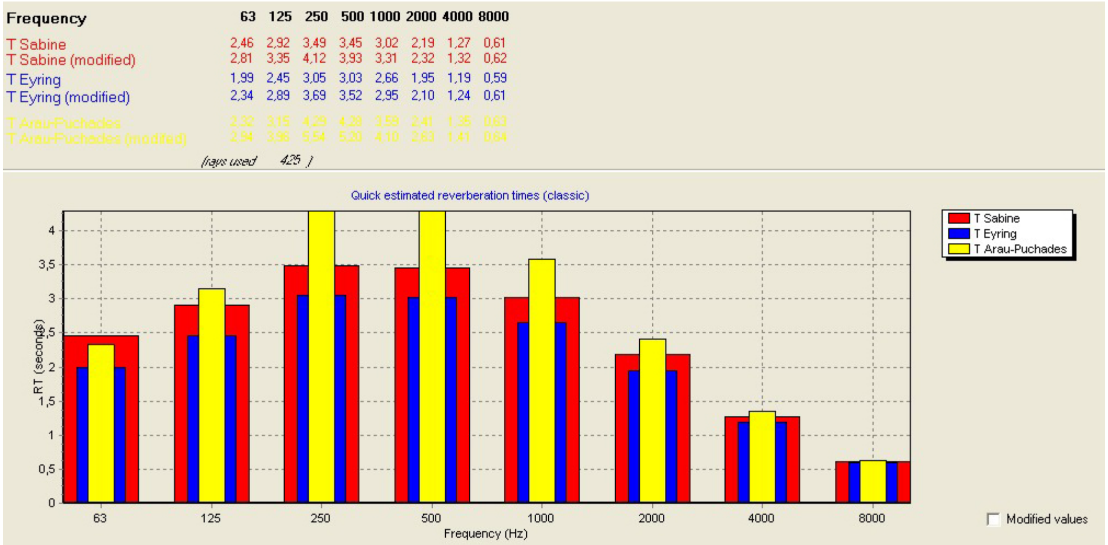


Figure 48. Estimated reverberation times of quick estimate for fully-occupied hall.

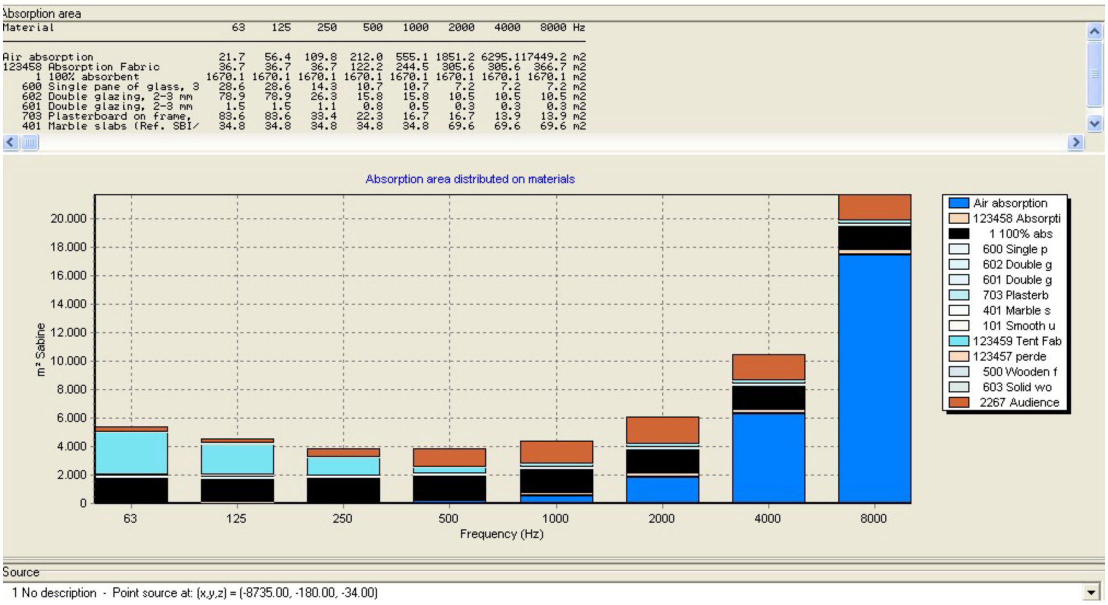


Figure 49. Material overview for the fully-occupied hall.

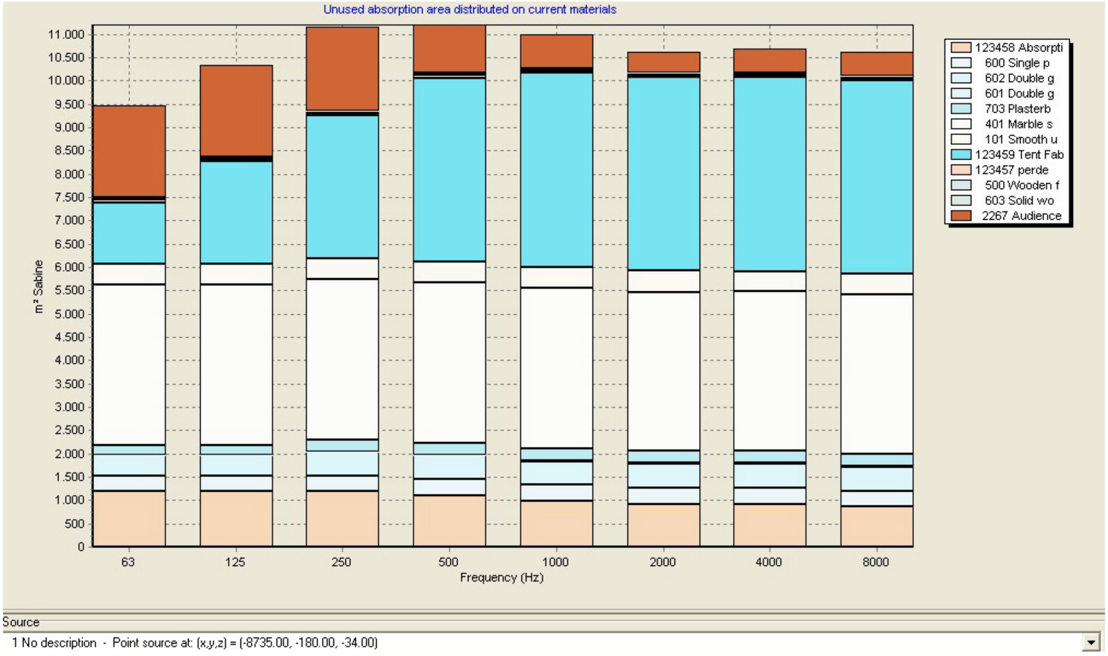


Figure 50. Unused absorption graph for the fully-occupied hall.

The quick estimation for the fully-occupied hall resulted that the reverberation time of the hall for mid frequencies is 3.62 s. However the much reliable method is the global estimation that should be taken into account. Examining the material overview and unused absorption graphs it is found that the audience creating the largest absorbing area at the mid frequencies, whereas the air absorption taking its place at high frequencies. On the other hand, the tent membrane and the travertine cladding are the largest reflective areas of the hall as in the case of unoccupied hall.

The next calculation is the global estimation including the energy curves, estimated reverberation times and the free path distribution graph. The results are given in Figure 51., Figure 52. and Figure 53.

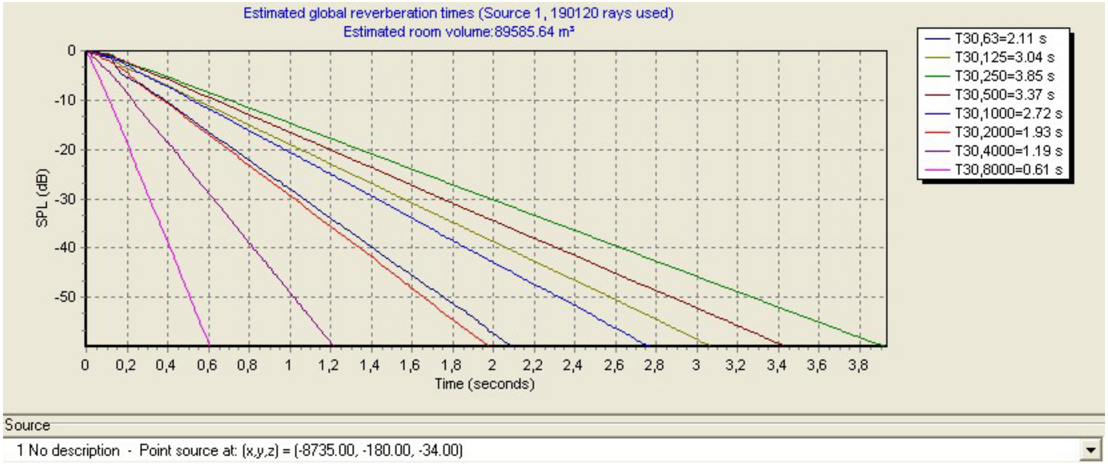


Figure 51. Energy curves for fully-occupied hall.

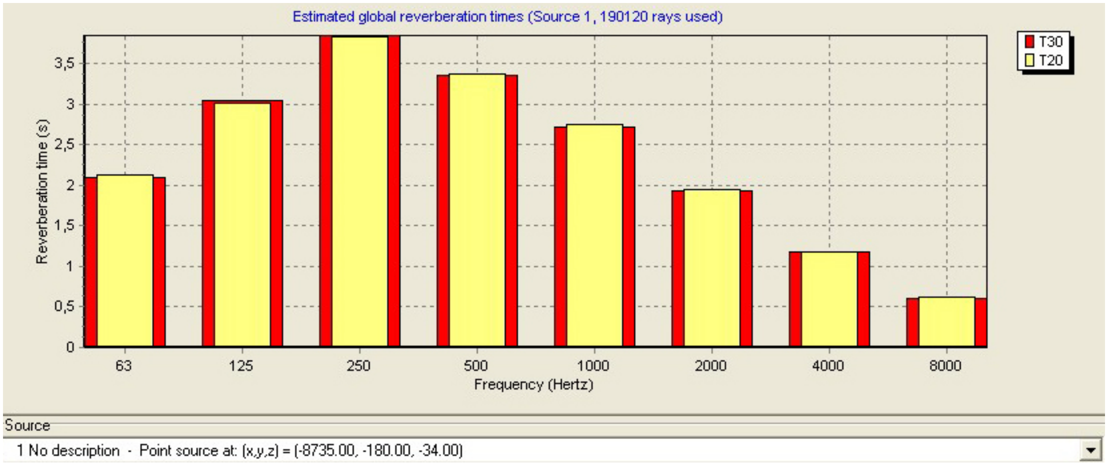


Figure 52. Estimated reverberation times of global estimate for fully-occupied hall.

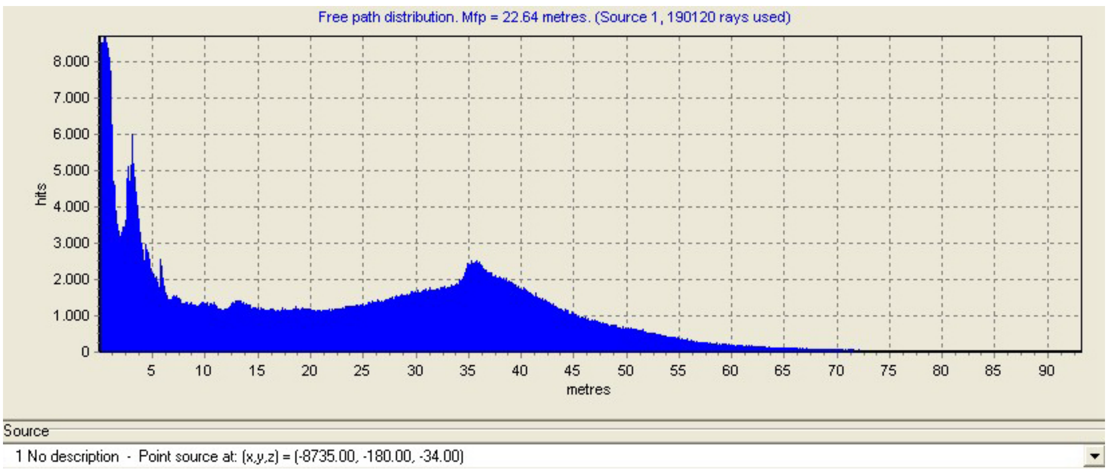


Figure 53. Free path distribution graph for fully-occupied hall.

The global estimation results show that the reverberation time of the hall for mid frequencies is 3.05 s, which is the average of reverberation times at 500 Hz and 1000 Hz. The value is higher than the limits of optimum reverberation times. The free path distribution graph is much alike the unoccupied hall, so there are jumps in the first five meters which is caused by the reflected sound at the closer seating area by the large cut surfaces of the ceiling membrane. The later reflections are characterized by a dense pattern and a smooth decay in the level of reflections. The unsmooth decay of the free path distribution graph is indicative of a poorly diffused sound field.

Global estimation results are continued with the grid response calculations for the selected receiver surfaces. The maps of different parameters including reverberation time (T30), early decay time (EDT), clarity (C80), definition (D50), lateral fraction (LF), sound pressure level distribution (SPL) and sound transmission index (STI) are obtained. These parameters are evaluated for 500 and 1000Hz. The results are represented by maps showing the overall distribution throughout the hall, which are followed by statistical graphs for each of the two frequency and seven measures, listed in the succeeding pages.

5.3.1.Reverberation Time (T30) Distribution Maps and Graphs

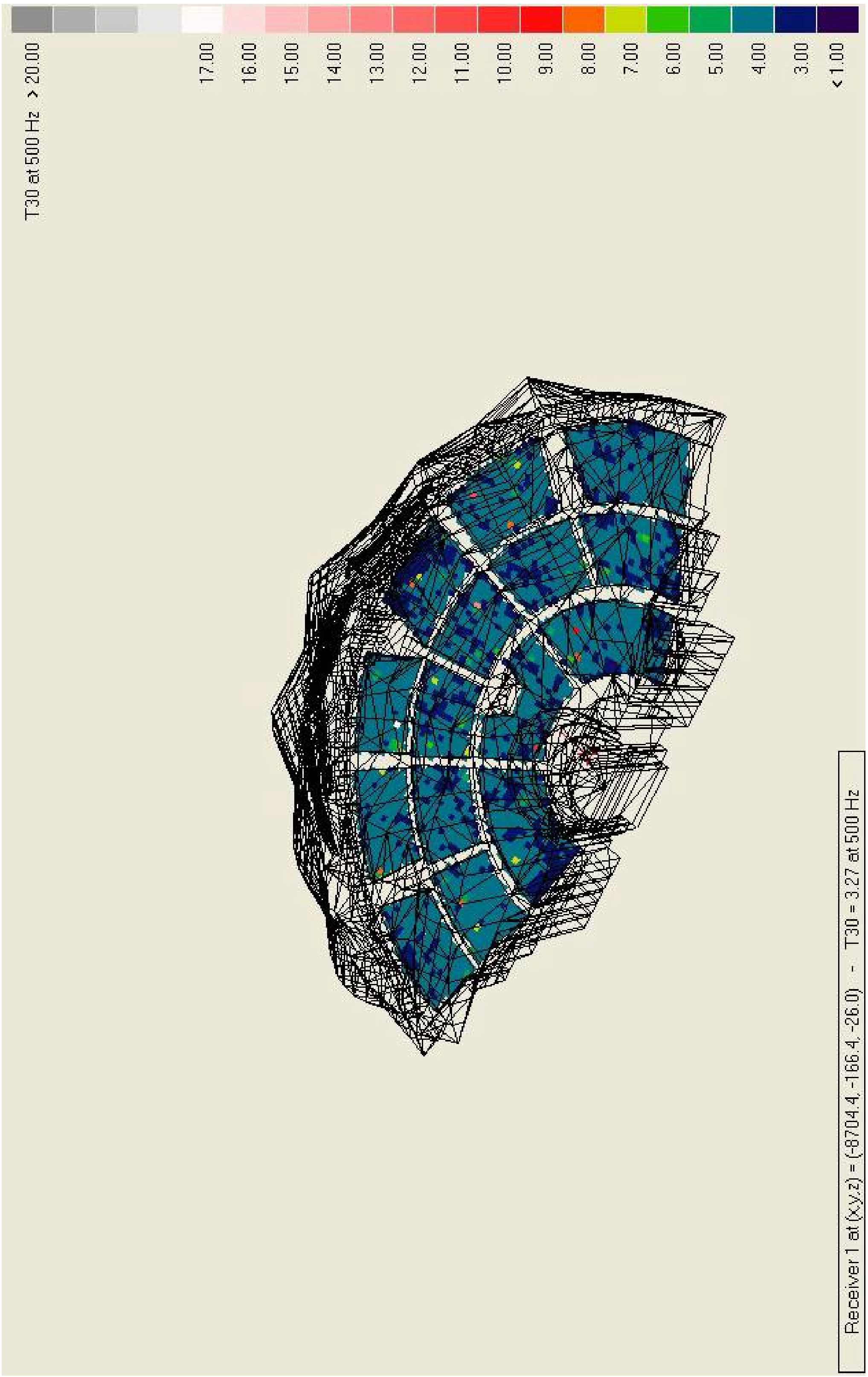


Figure 54. Reverberation time distribution map for 500 Hz and for the fully-occupied hall.

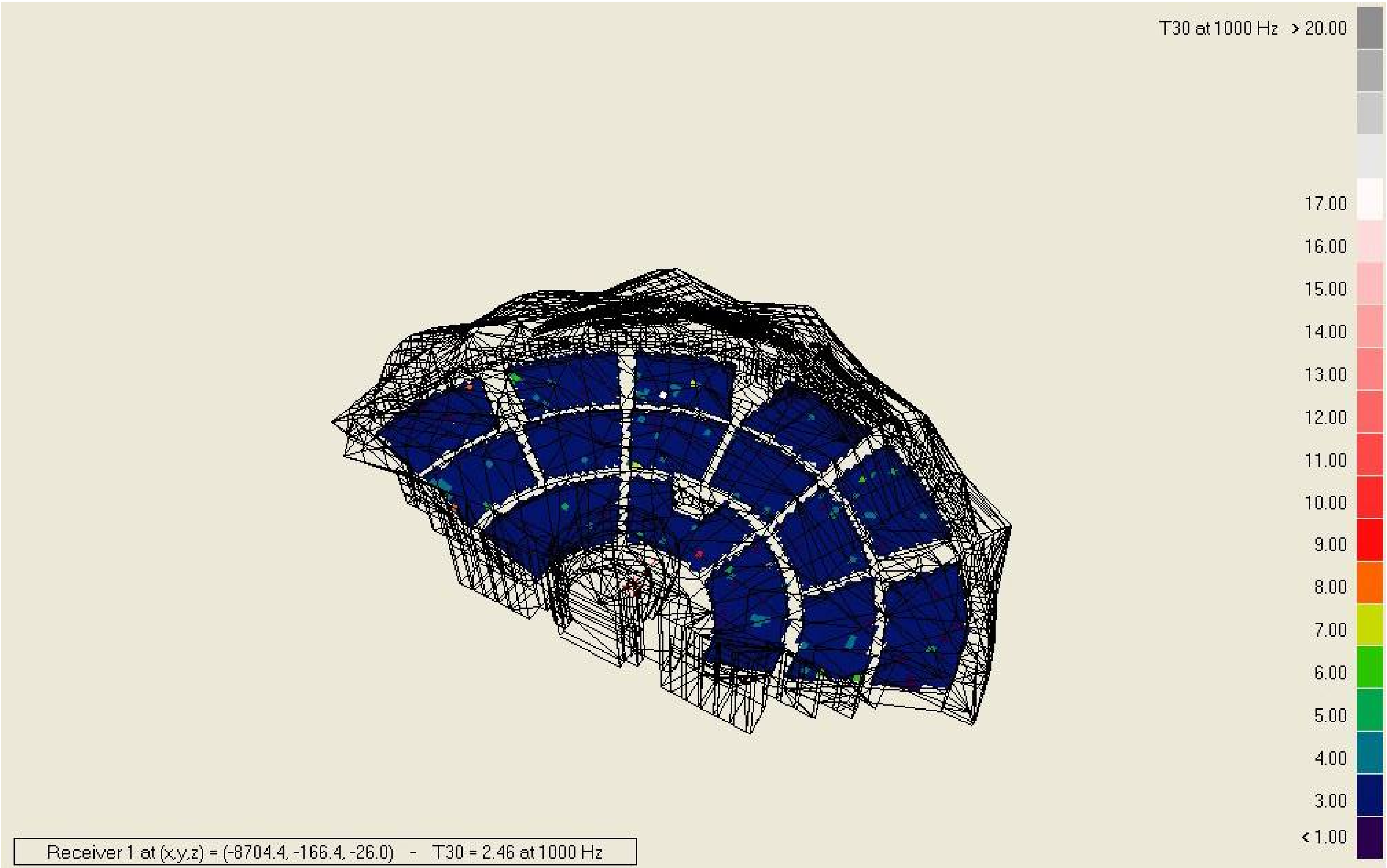


Figure 55. Reverberation time distribution map for 1000 Hz and for the fully-occupied hall.

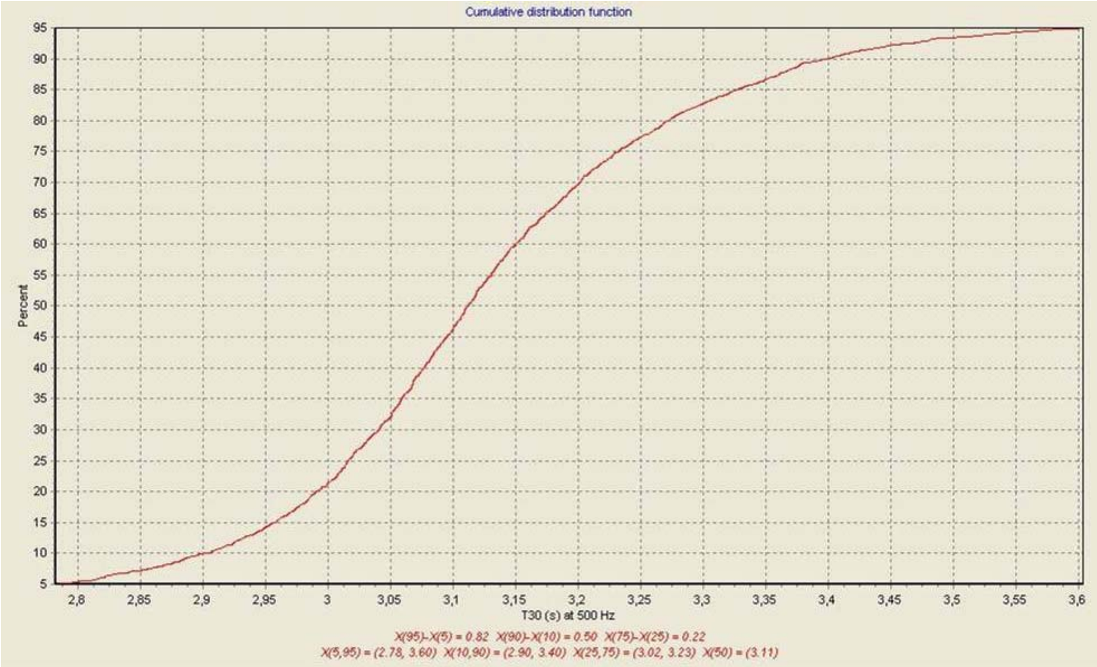


Figure 56. Reverberation time cumulative distribution graph for 500 Hz and for the fully-occupied hall.

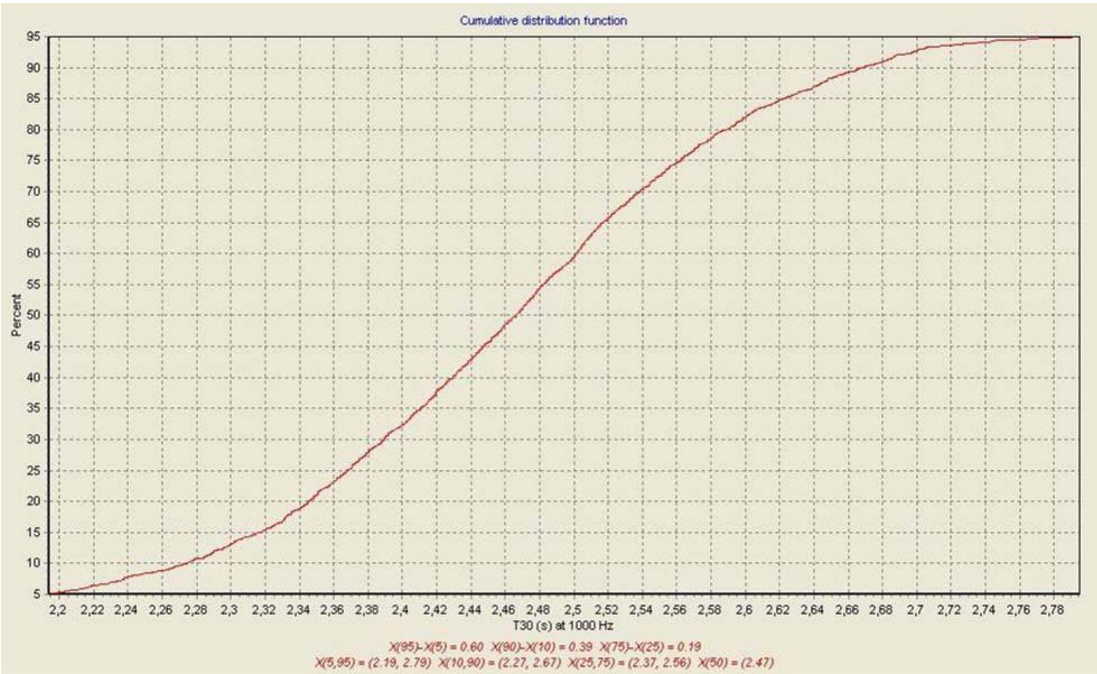


Figure 57. Reverberation time cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.2. Early Decay Time (EDT) Distribution Maps and Graphs

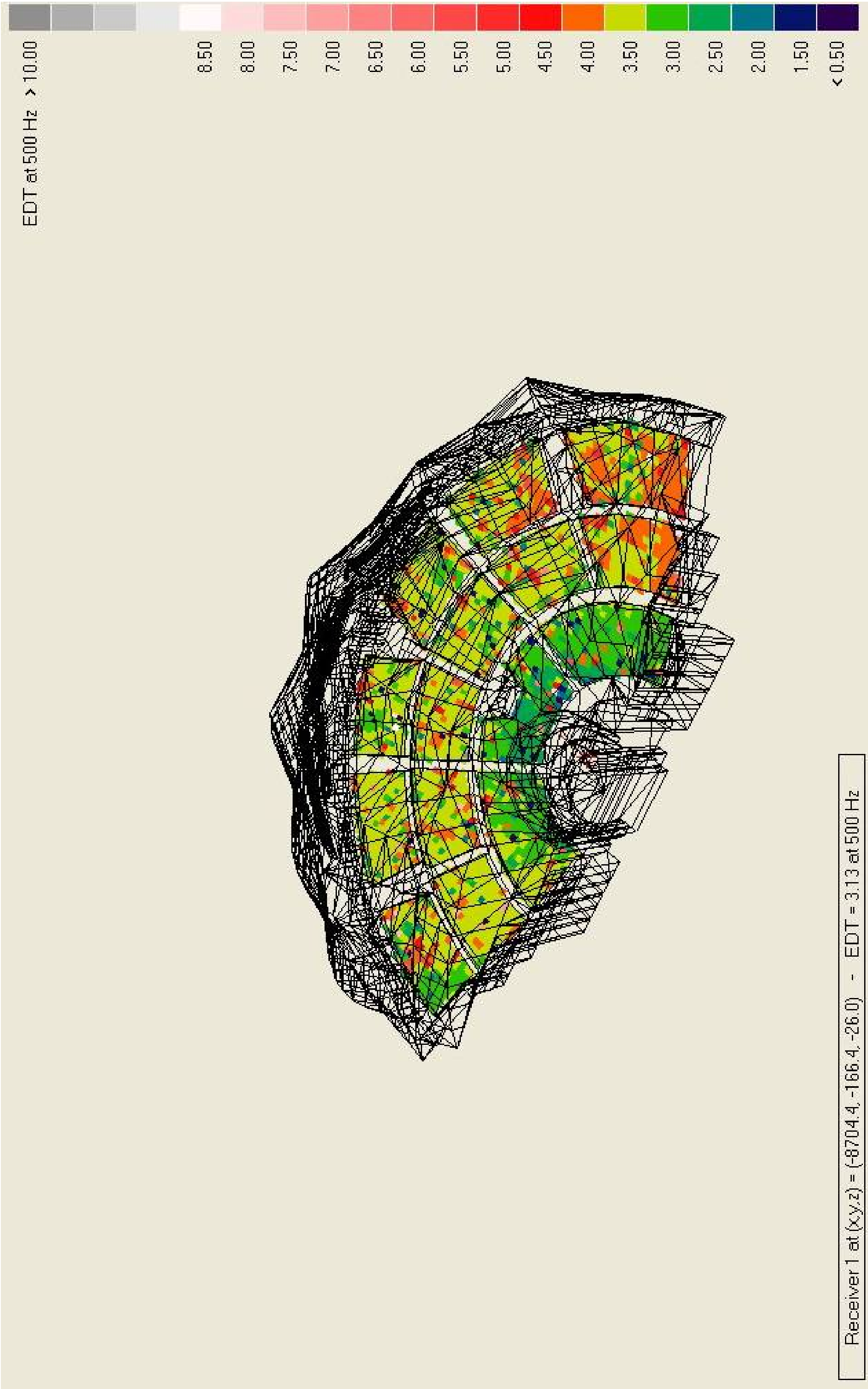


Figure 58. Early decay time distribution map for 500 Hz and for the fully-occupied hall.

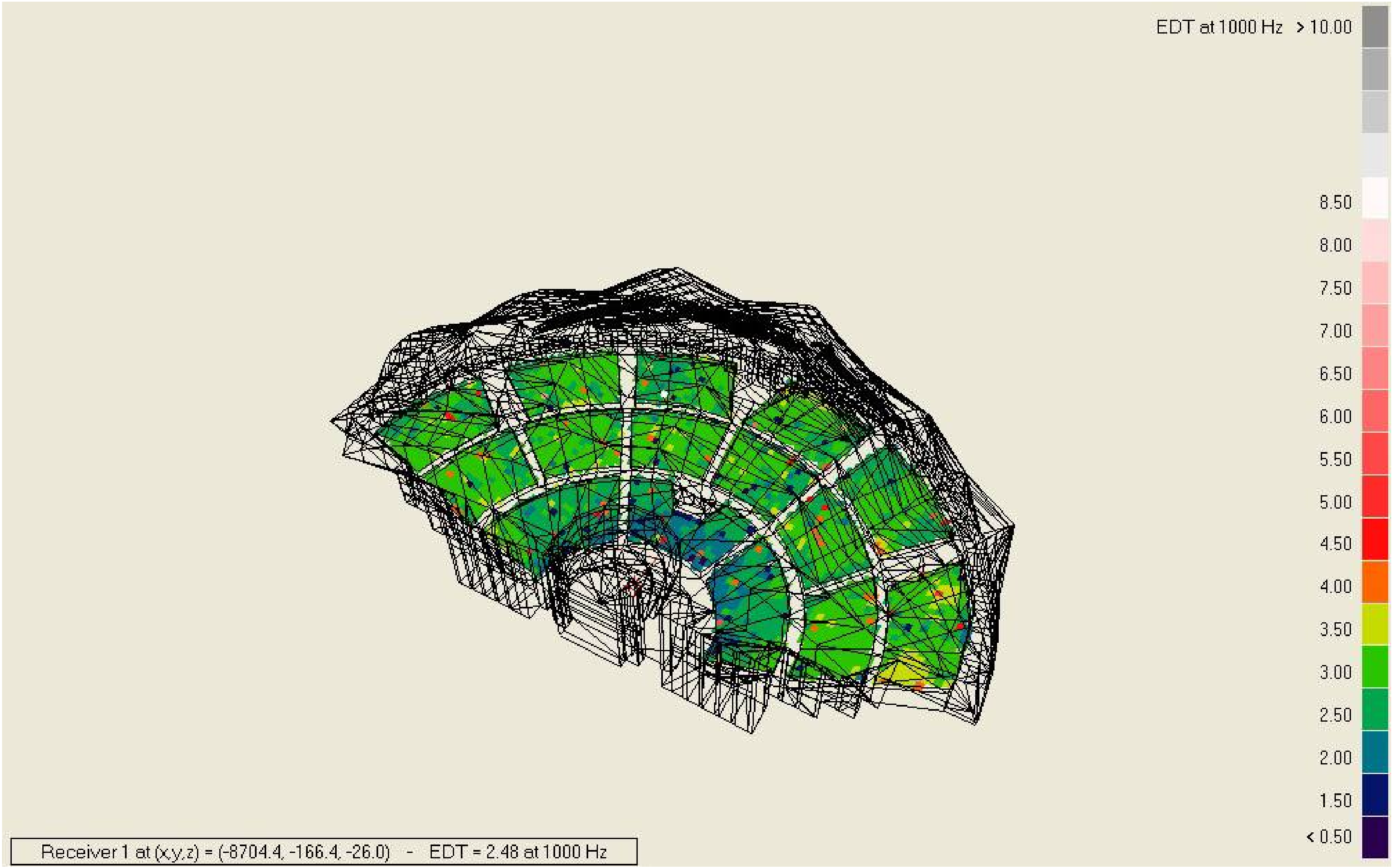


Figure 59. Early decay time distribution map for 1000 Hz and for the fully-occupied hall.

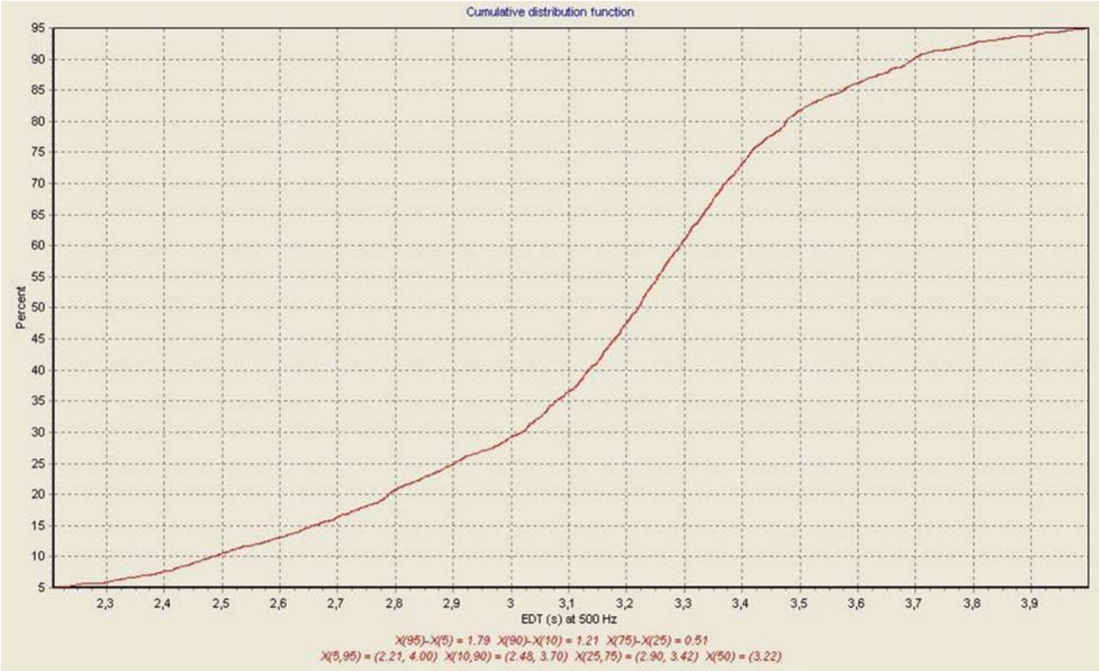


Figure 60. Early decay time cumulative distribution graph for 500 Hz and for the fully-occupied hall.

Figure 61. Early decay time cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.3. Clarity (C80) Distribution Maps and Graphs

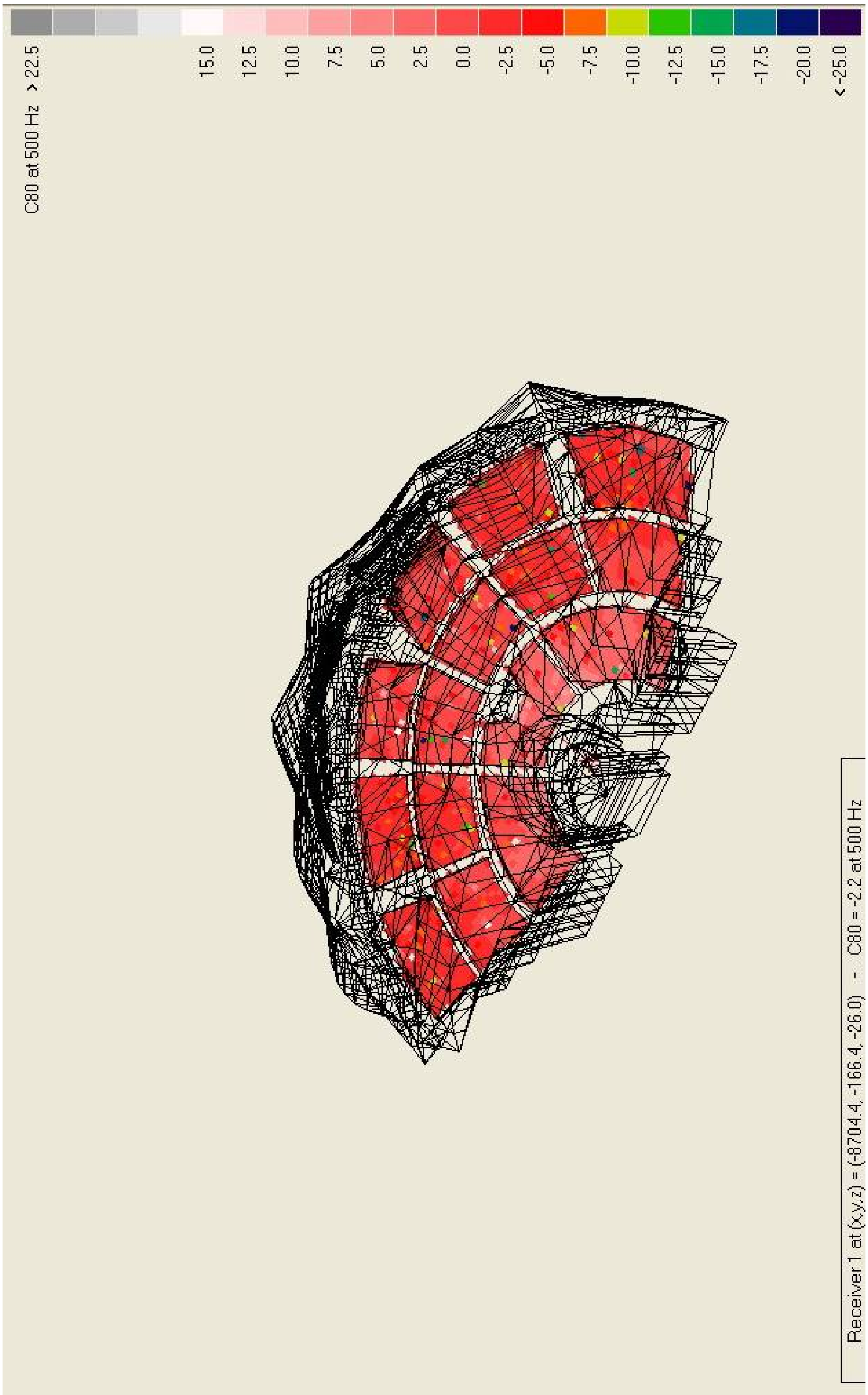


Figure 62. Clarity distribution map for 500 Hz and for the fully-occupied hall.

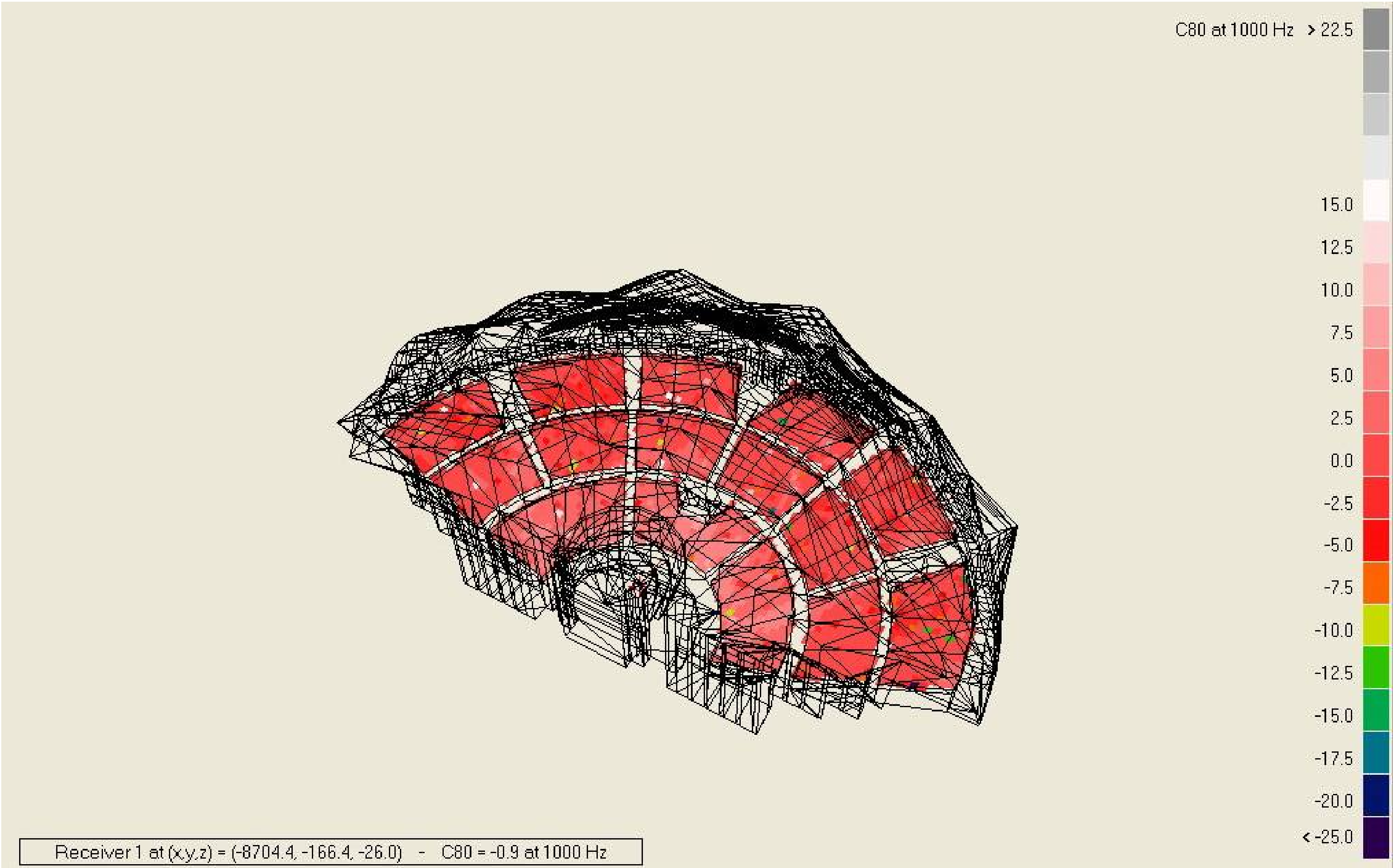


Figure 63. Clarity distribution map for 1000 Hz and for the fully-occupied hall.

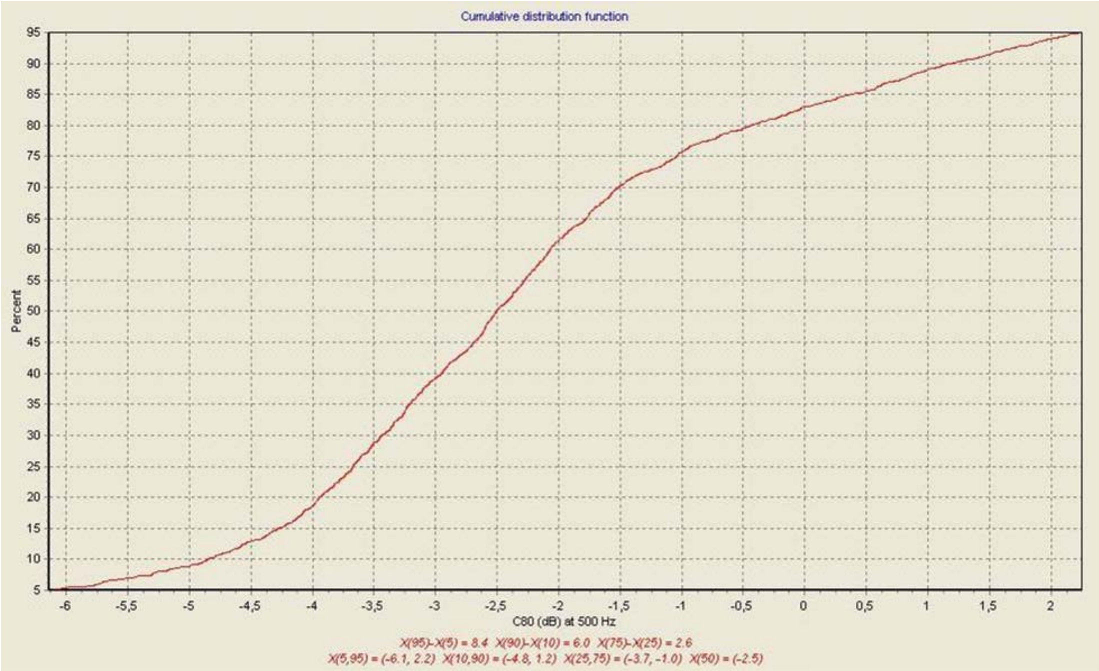


Figure 64. Clarity cumulative distribution graph for 500 Hz and for the fully-occupied hall.

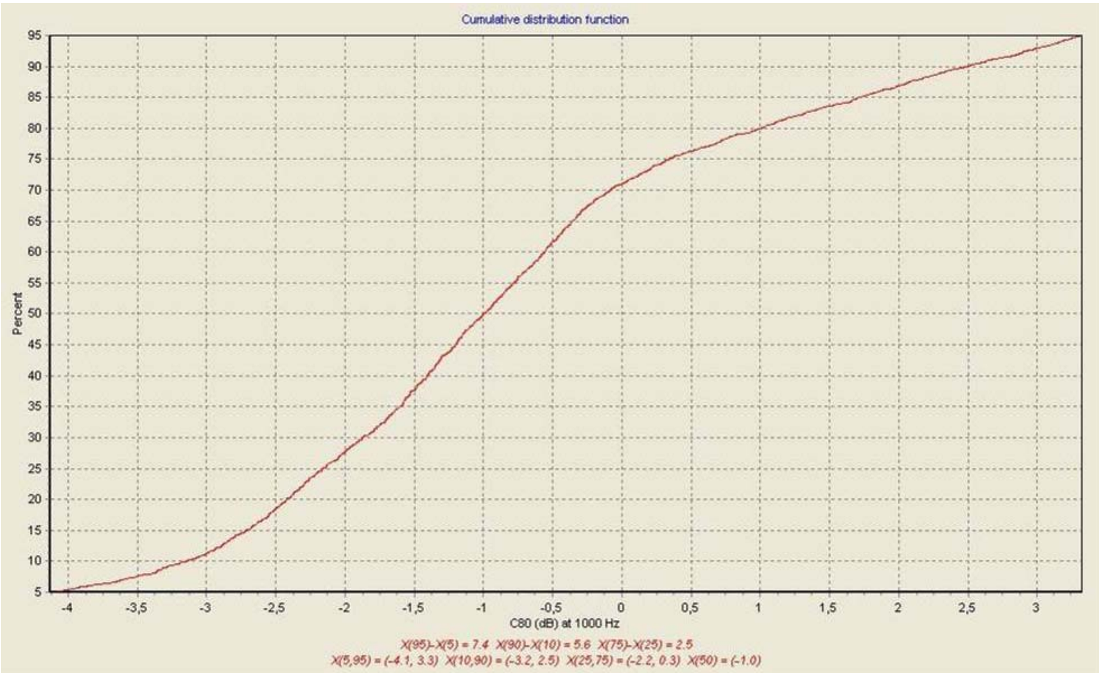


Figure 65. Clarity cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.4. Definition (D50) Distribution Maps and Graphs

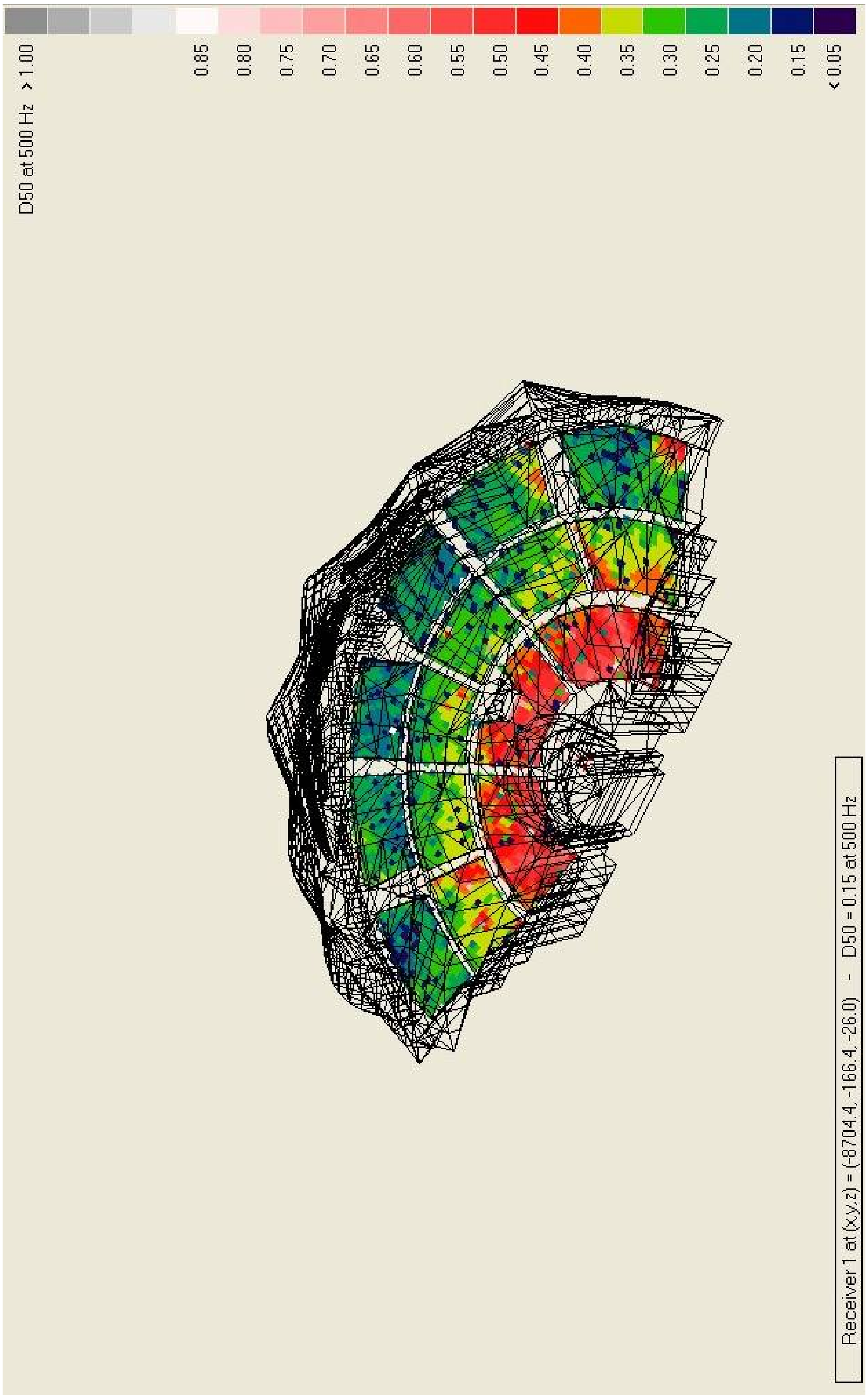


Figure 66. Definition distribution map for 500 Hz and for the fully-occupied hall.

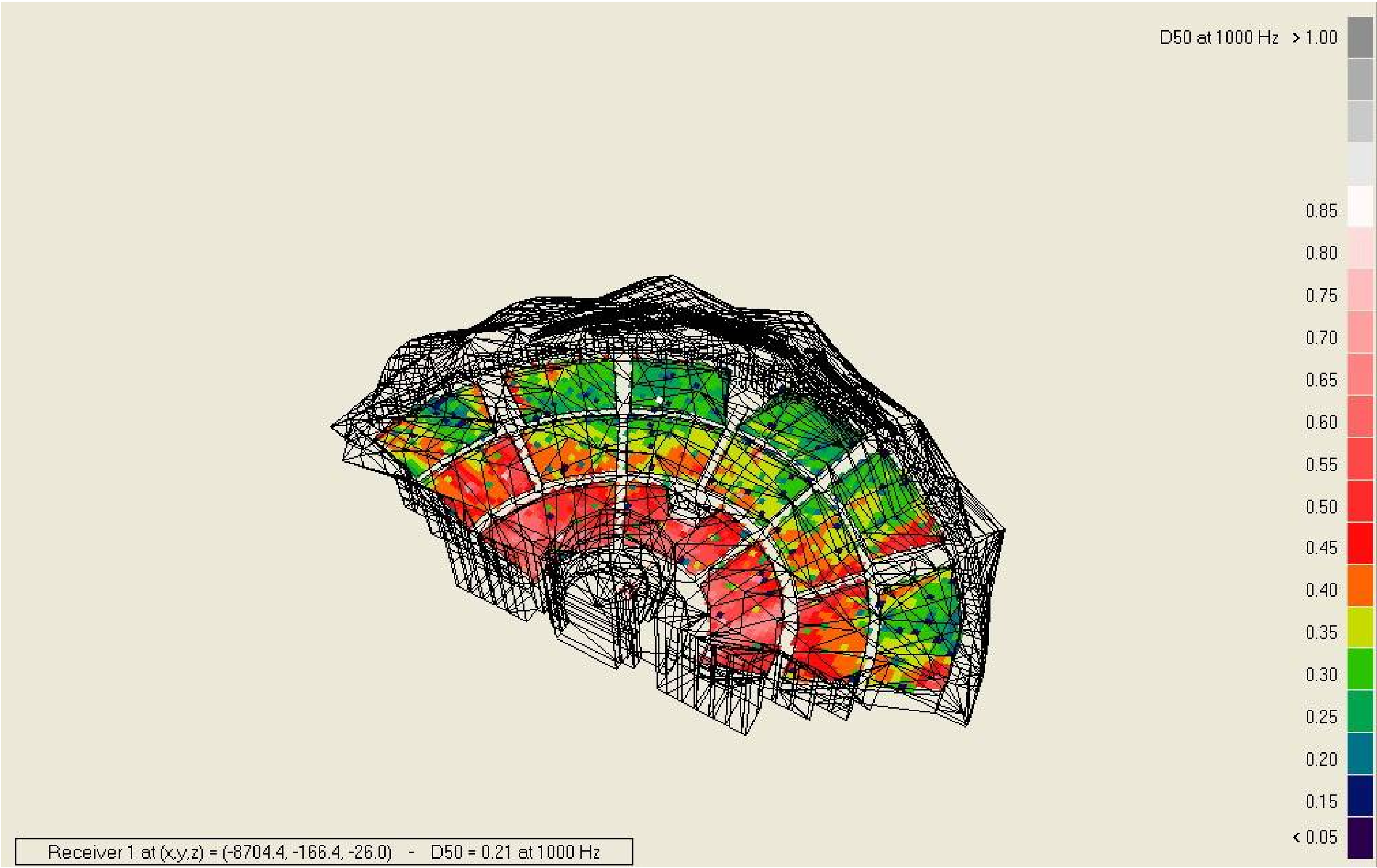


Figure 67. Definition distribution map for 1000 Hz and for the fully-occupied hall.

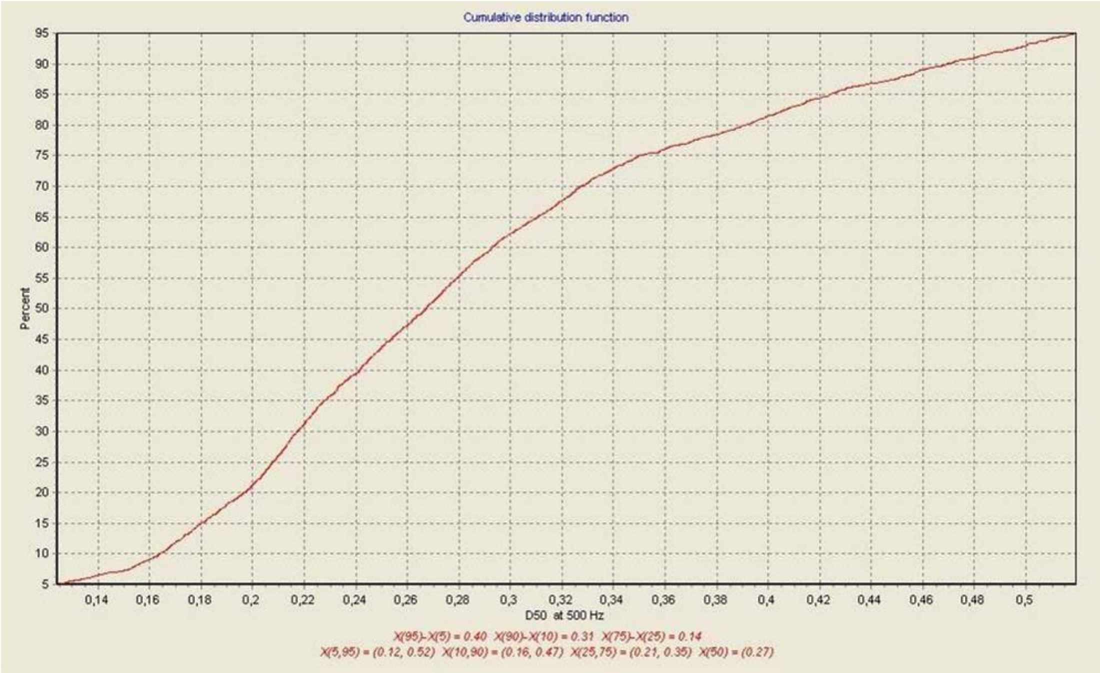


Figure 68. Definition cumulative distribution graph for 500 Hz and for the fully-occupied hall.

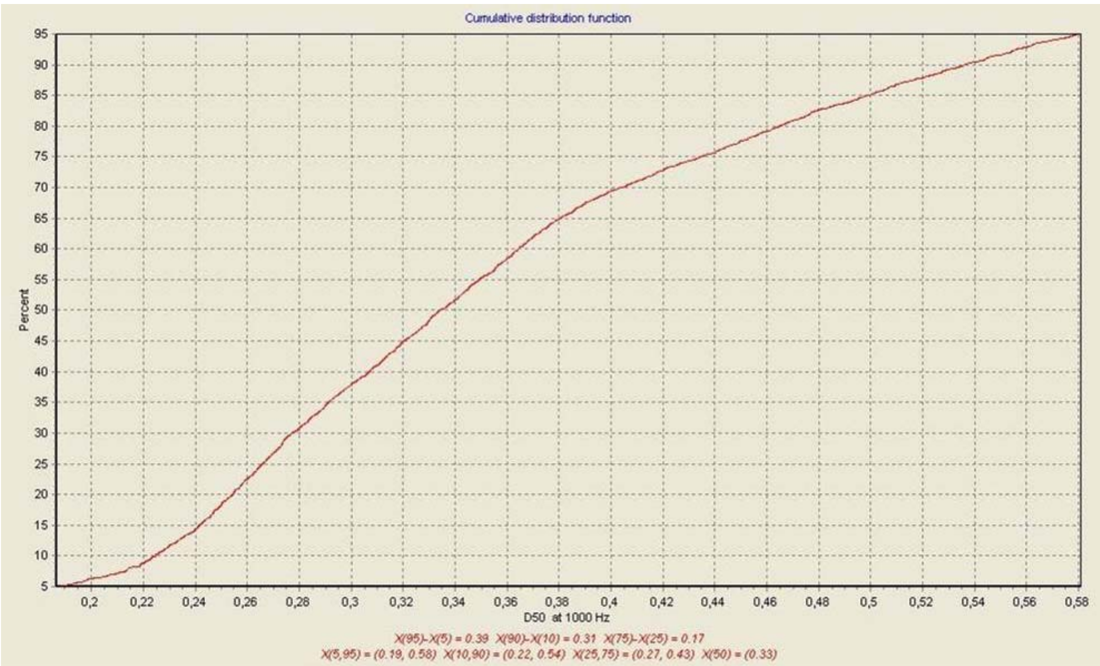


Figure 69. Definition cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.5. Lateral Fraction (LF) distribution Maps and Graphs

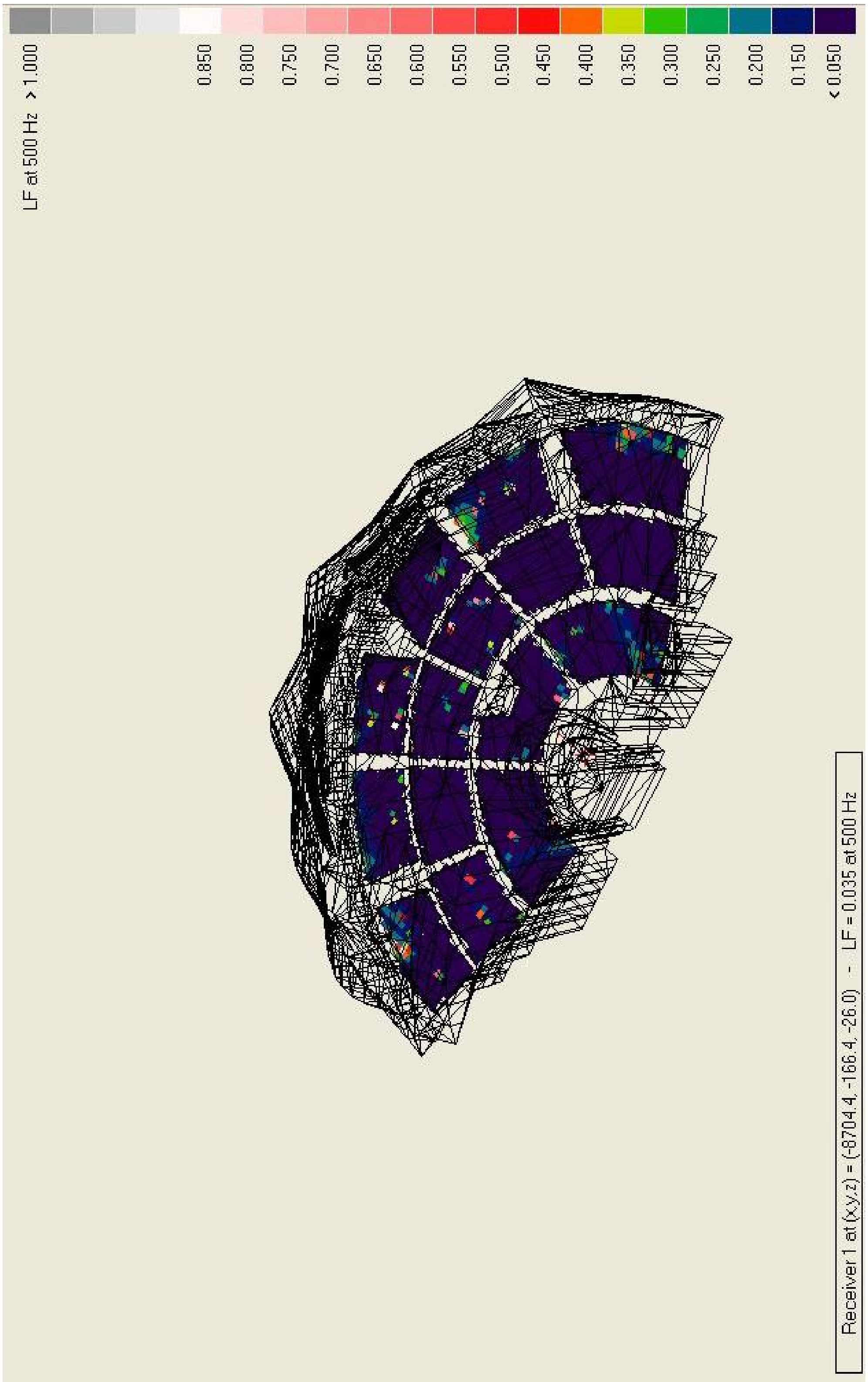


Figure 70. Lateral fraction distribution map for 500 Hz and for the fully-occupied hall.

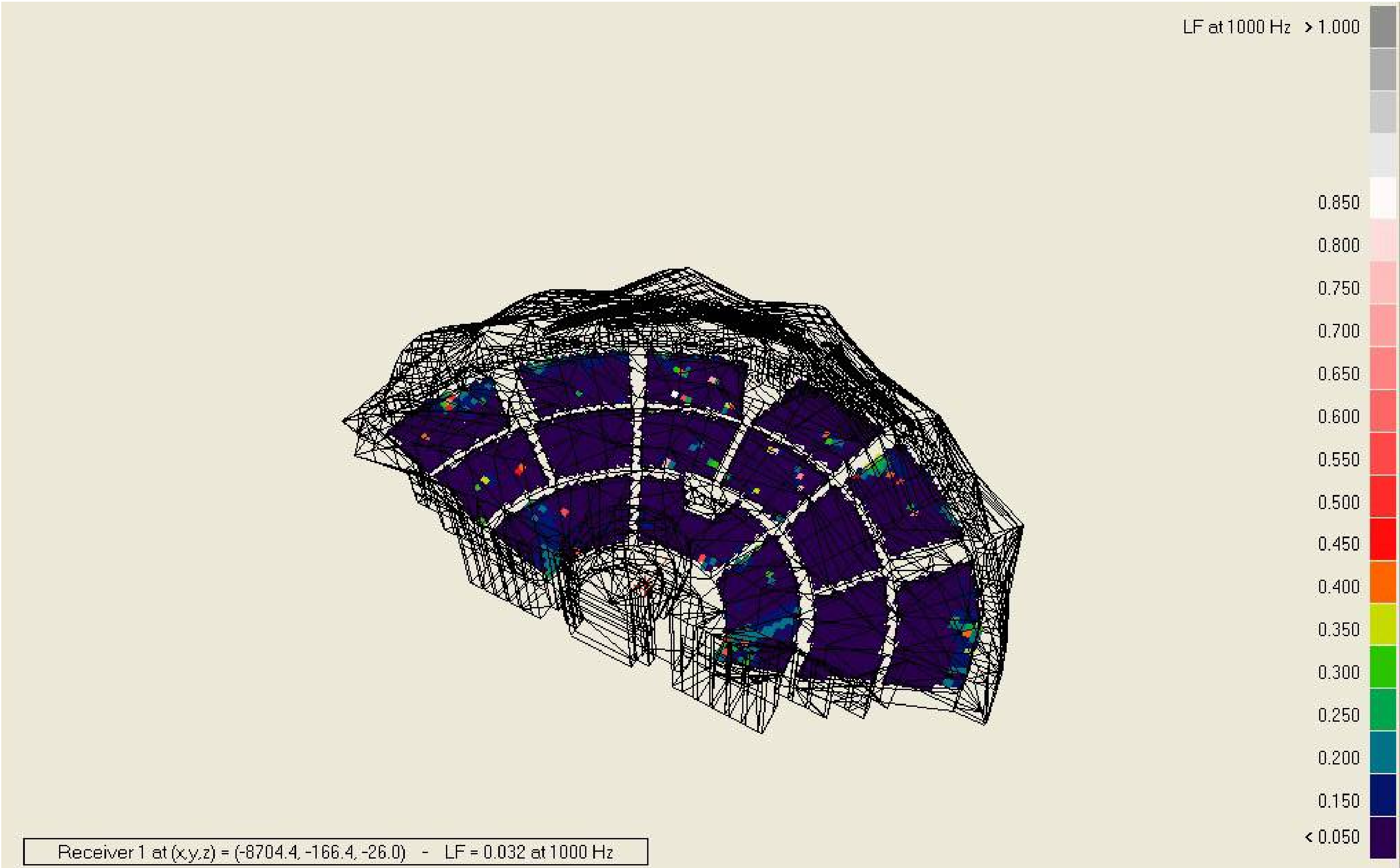


Figure 71. Lateral fraction distribution map for 1000 Hz and for the fully-occupied hall.

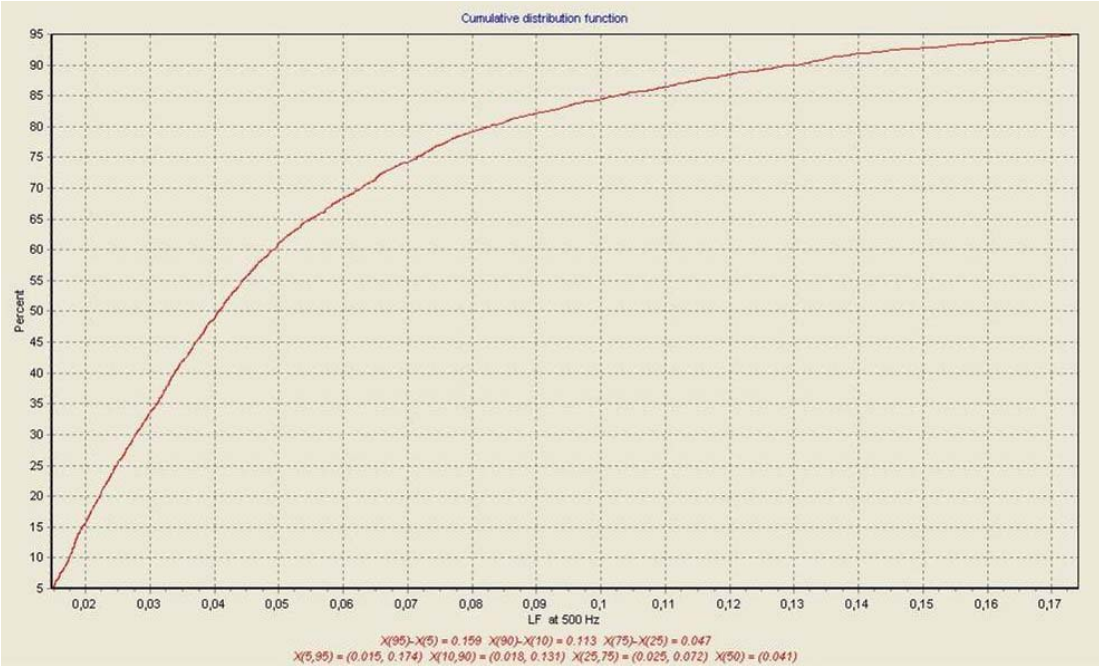


Figure 72. Lateral fraction cumulative distribution graph for 500 Hz and for the fully-occupied hall.

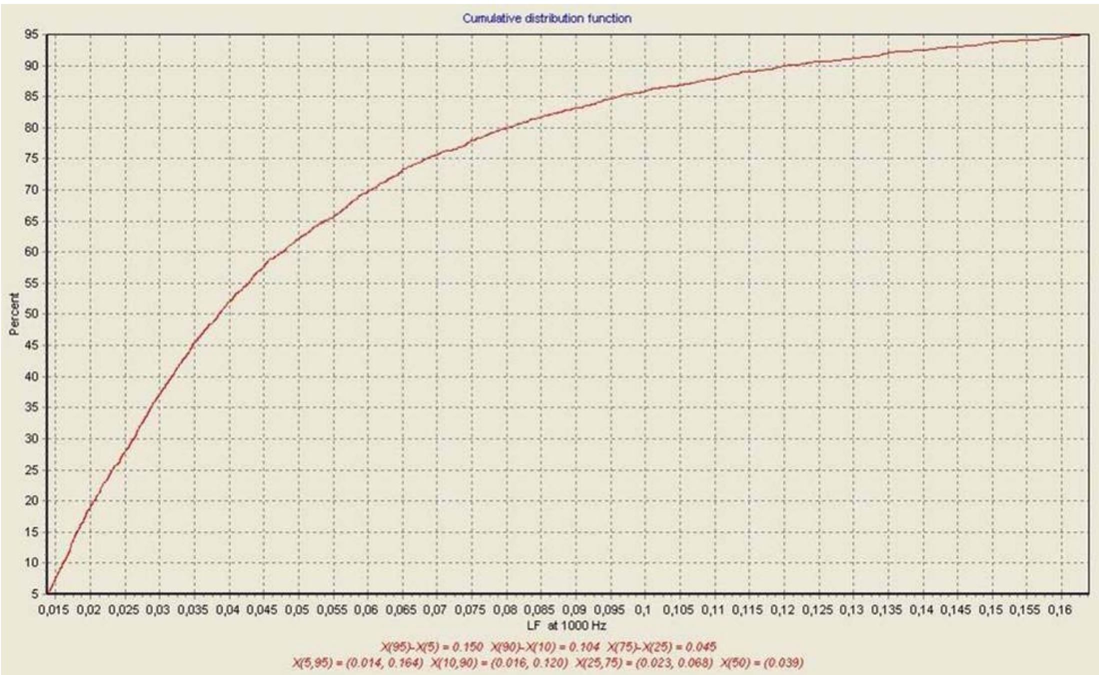


Figure 73. Lateral fraction cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.6. Sound Pressure Level (SPL) Distribution Maps and Graphs

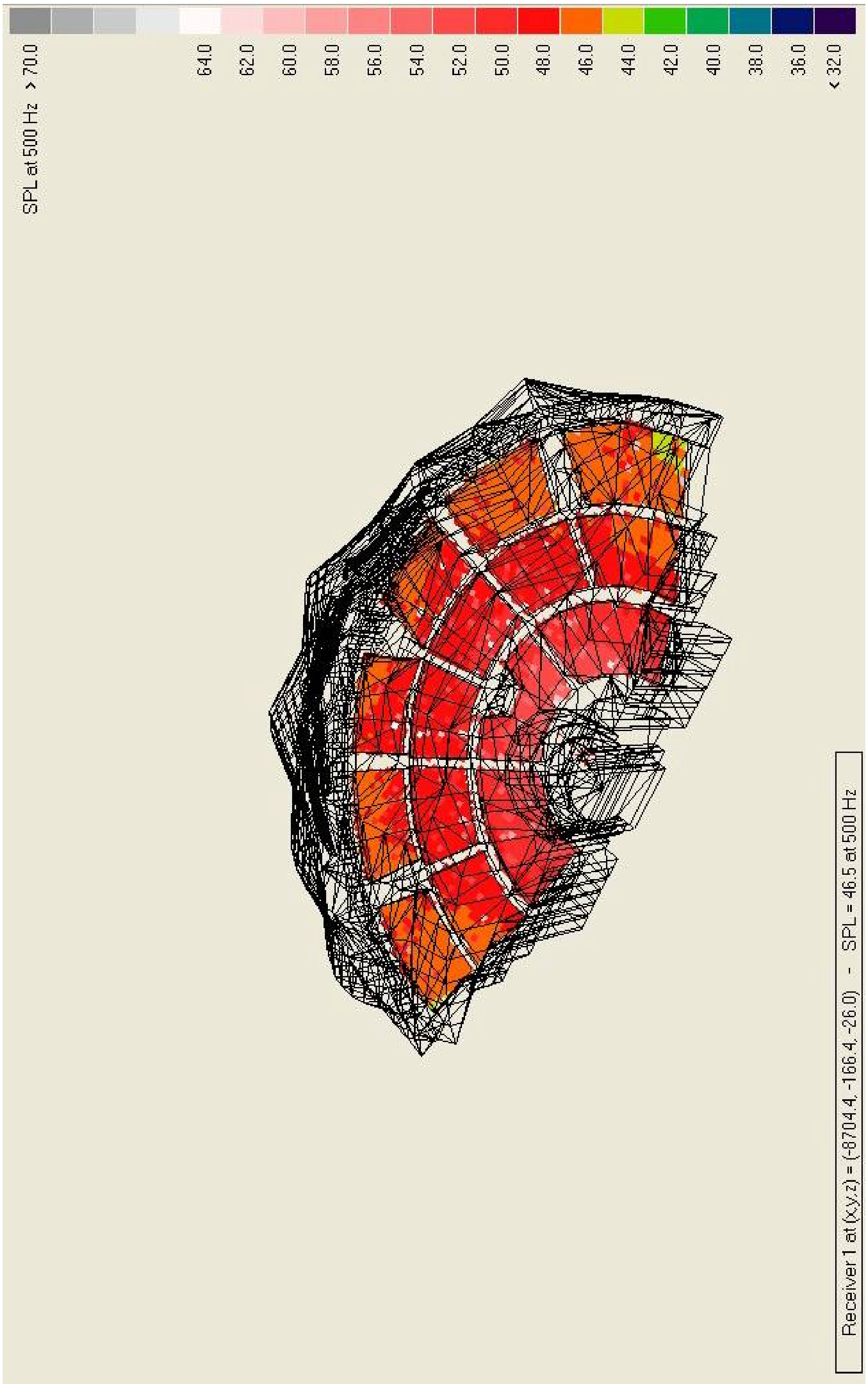


Figure 74. Sound pressure level distribution map for 500 Hz and for the fully-occupied hall.

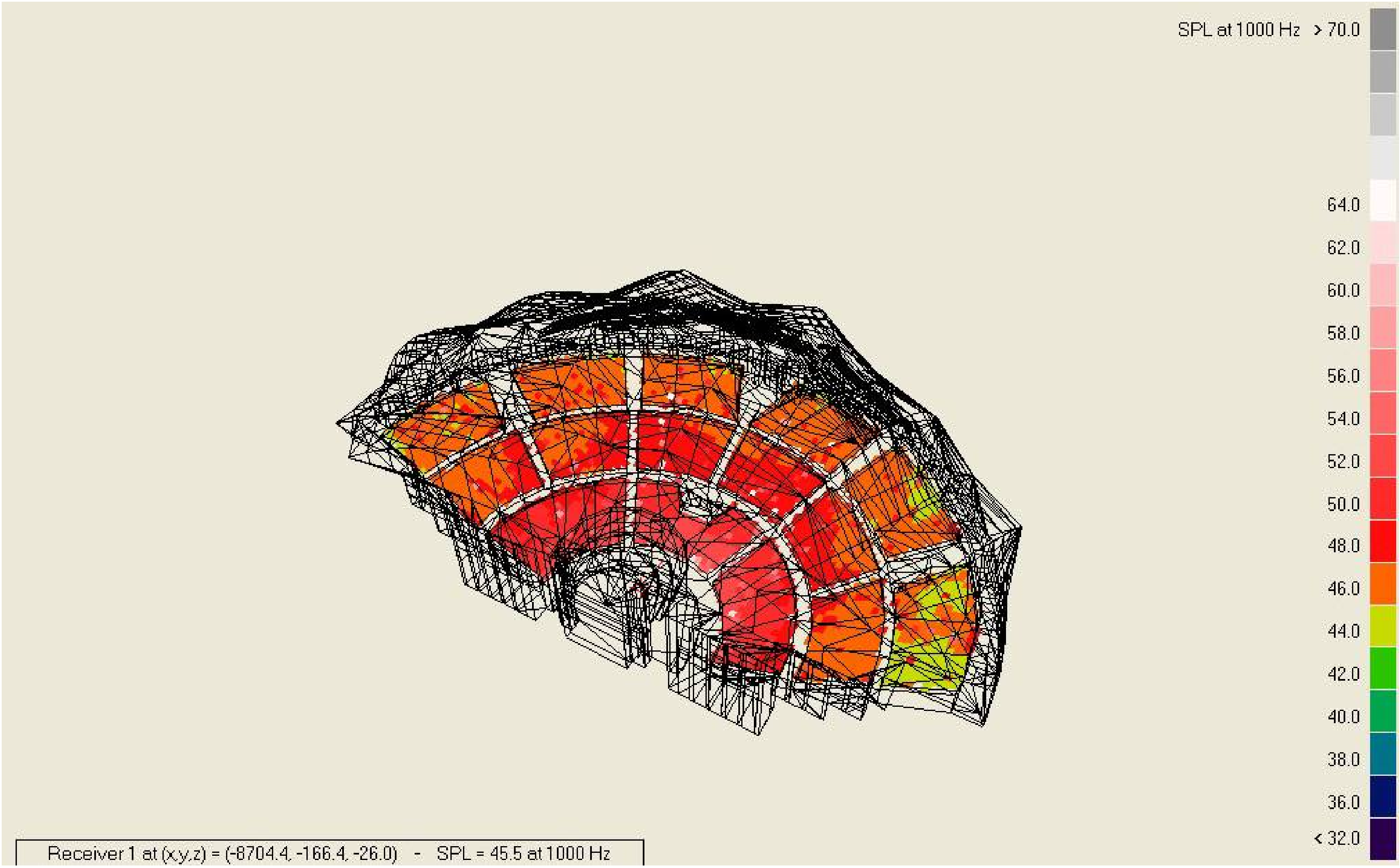


Figure 75. Sound pressure level distribution map for 1000 Hz and for the fully-occupied hall.

Figure 76. Sound pressure level cumulative distribution graph for 500 Hz and for the fully-occupied hall.

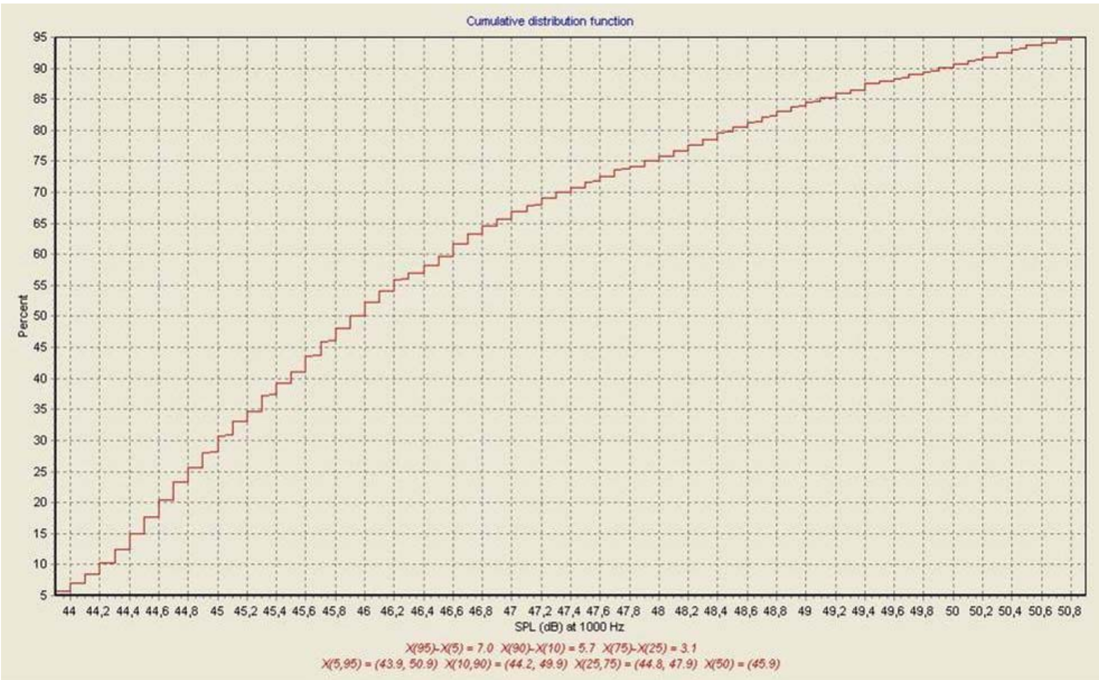


Figure 77. Sound pressure level cumulative distribution graph for 1000 Hz and for the fully-occupied hall.

5.3.7. Sound Transmission Index Distribution Maps and Graphs

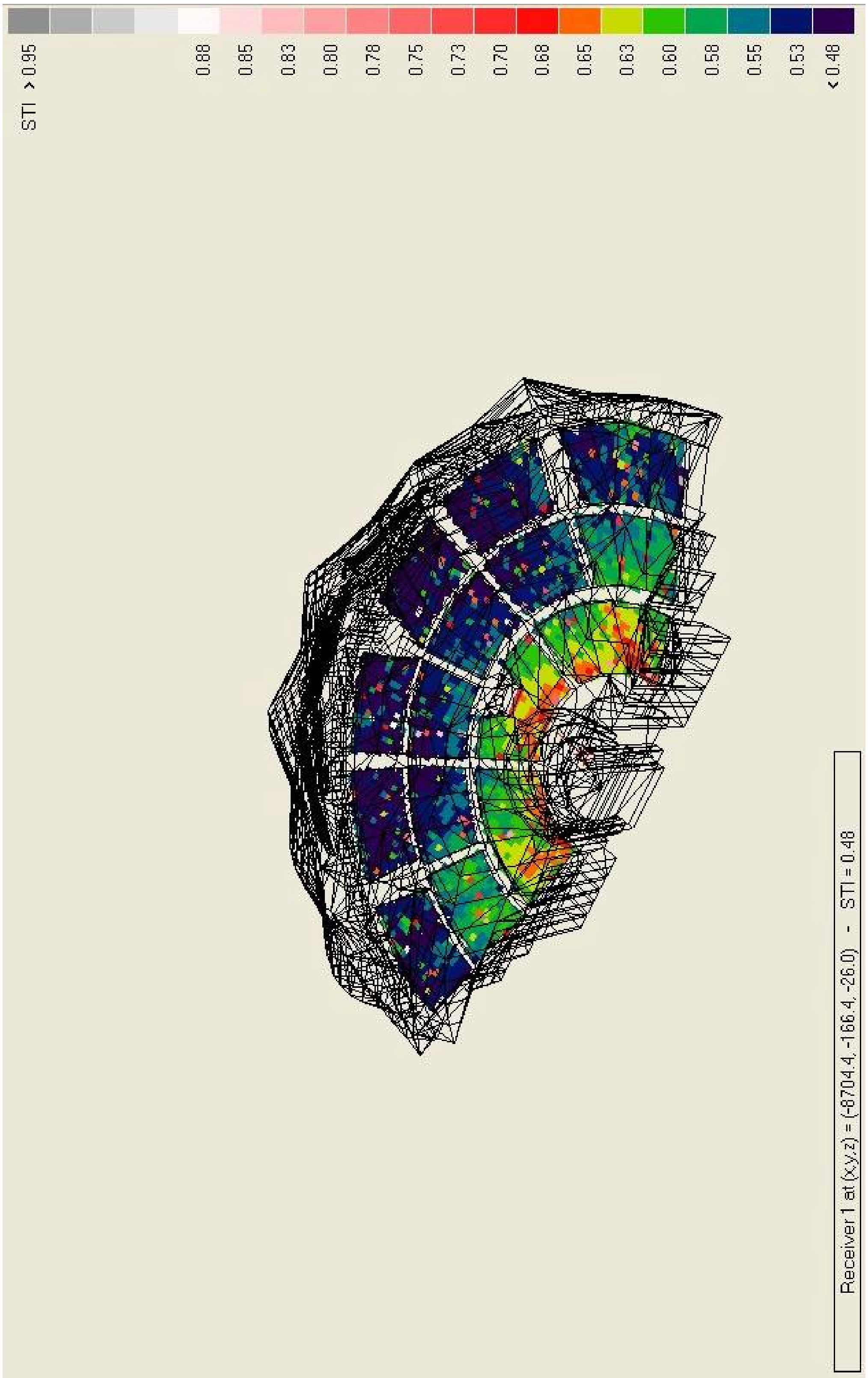


Figure 78. Sound transmission index (STI) distribution map for the fully-occupied hall.

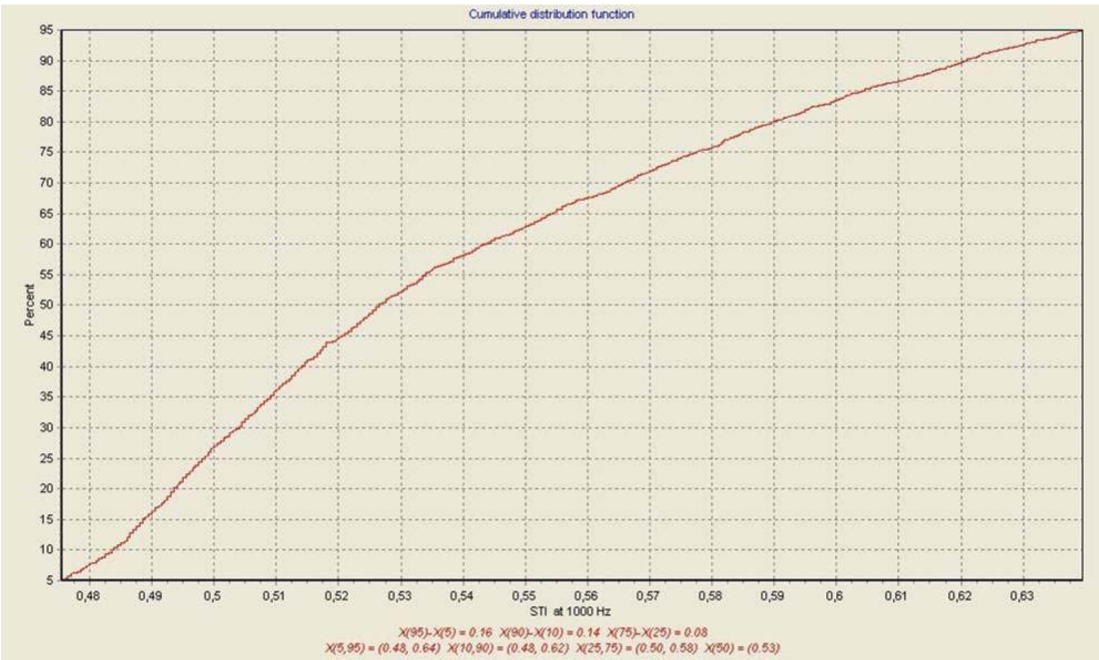


Figure 79. Sound transmission index (STI) cumulative distribution graph for the fully-occupied hall.

The grid response results are beginning with the reverberation time distribution maps, different from the unoccupied hall in that part the statistical graphs of the results are also involved. When the Figure 54., Figure 55., Figure 56. and Figure 57. are analyzed, the uneven distribution of the results can be seen in the occupied hall as well. The results are ranging from 2.8 to 3.6 s according to the cumulative distribution function, whereas 3.6 s is covering the 95% of the hall for 500Hz. This value is also much higher than the required measure, especially for the speech activities. For 1000 Hz there is a much even distribution with 2.81 s for 95% of the hall. The focuses of the sound are less than the unoccupied case due to the audience absorption, however the echoes are still in disturbing amounts.

Analyzing the Figure 58., Figure 59., Figure 60. and Figure 61. it is observed that the early decay time measures are ranging in between 2.3 to 4 s, while 95% of the values are showing to be 4 s for 500Hz. The map illustrates that the values are better in the front tiers especially at the mid fronts and rising towards the back tiers. Besides the focuses all over the hall, the highest values occur at the back sides as well. The values at 1000 Hz are showing the similar sound distribution, with 3.15 s of 95%. These mid frequency values for the EDT are also higher than the maximum limit of the optimum range. Being a part of the uneven distribution of sound in the hall, the focuses are not the only defect. There are also dead points in compare to the live areas at the hall with reverberation times lower than 1s.

The clarity cumulative distribution maps and graphs in the Figure 62., Figure 63., Figure 64. and Figure 65. picture that the values are ranging in between -6 to 2.2 dB, which is including both the acceptable and unacceptable measures for 500 Hz and ranging in between -4 to 3.3 dB for 1000 Hz again involving both fair and bad measures. Analyzing the maps it is concluded that the better values are at the front tiers and at the center of the mid tiers. However the excessive values including both the lowest and highest measures could be seen throughout the hall from the maps apparently at some specific points. These peaks of low and high values are sometimes very closer to each other as in the case of center rows of the mid tears. In this example, on the other hand, except these problematic places the area shows good results when compared to the hall in general.

Analyzing the Figure 66., Figure 67., Figure 68. and Figure 69., the definition illustrates one of the worst distributions of the sound throughout the hall. This implies that the intelligibility of the details of speech, besides the sensation of details in music is insufficient for much of the places. The values are ranging in between 0.14 to 0.55 for 500 Hz with 0.55 at majority and in between 0.2 to 0.58 for 1000 Hz with 0.58 at majority. This shows that most of the places are out of the optimum range. The values are much higher than the required ones at the front tiers, whereas it reaches to the acceptable values at some places of the mid and back tiers. To conclude, the uneven distribution is the most important cause for making the parameter not convincing for both speech and music performances.

The next parameter to be mentioned is the lateral fraction. The values are ranging in between 0.02 to 0.17 for 500 Hz and 0.015 to 0.163 for 1000 Hz. Examining the distribution maps and graphs from the Figure 70., Figure 71., Figure 72. and Figure 73., it is found that the LF values of the hall in general is smaller than 0.15 in both frequencies which is not sufficient for the concert halls and for other activities as well. The better places throughout the hall considering the lateral fraction are back and front tier sides, and the back rows of the mid sides.

Analyzing the Figure 74., Figure 75., Figure 76. and Figure 77., it is found that the sound pressure level distribution illustrates high peak values at very different points of the hall, which is caused by the sound focusing at these locations. For 500 Hz the values are in between 44.8 to 51.6 dB and for 1000 Hz it is in between 44 to 50.8 dB, which shows a difference greater than 10 dB that could be tolerated. The decrease in sound pressure level of approximately 10 dB means that the sound can not reach at sufficient amounts to all of the seat locations. Looking at the maps, it is obvious that the sound pressure begins decreasing at the mid sides and the decrease continues at all over the back tiers, certainly worst at the back sides.

The final parameter of the grid responses given in the Figure 78. and Figure 79. is the sound transmission index, which is directly related with the speech and the performances related to it. The values are ranging from 0.48 to 0.63, which are corresponding to the fair class for the parameter in general. By the way, the results to some extent are better than the unoccupied hall, which is again related to the audience absorption mostly at the higher frequencies. The maps illustrate that the value is best at the front tiers corresponding to the good class, and in very few points at the mid first row it is classified as excellent. The sides of the mid tiers are classified as fair and better than the centre of the mid tiers. Coming to the back tiers the values continue to drop and in some parts mostly at the mid parts of the last two rows it is evaluated as bad and unacceptable for STI.

The final display of the simulation for the fully-occupied hall is the reflector coverage which investigates whether the receiver area is covered by the reflectors or not. Moreover it gives clues about how dense the reflected early and late sound reaches to the receiver areas. The related distribution of the sound through the ceiling and diffuser surfaces are shown in the Figure 80., Figure 81., and Figure 82.

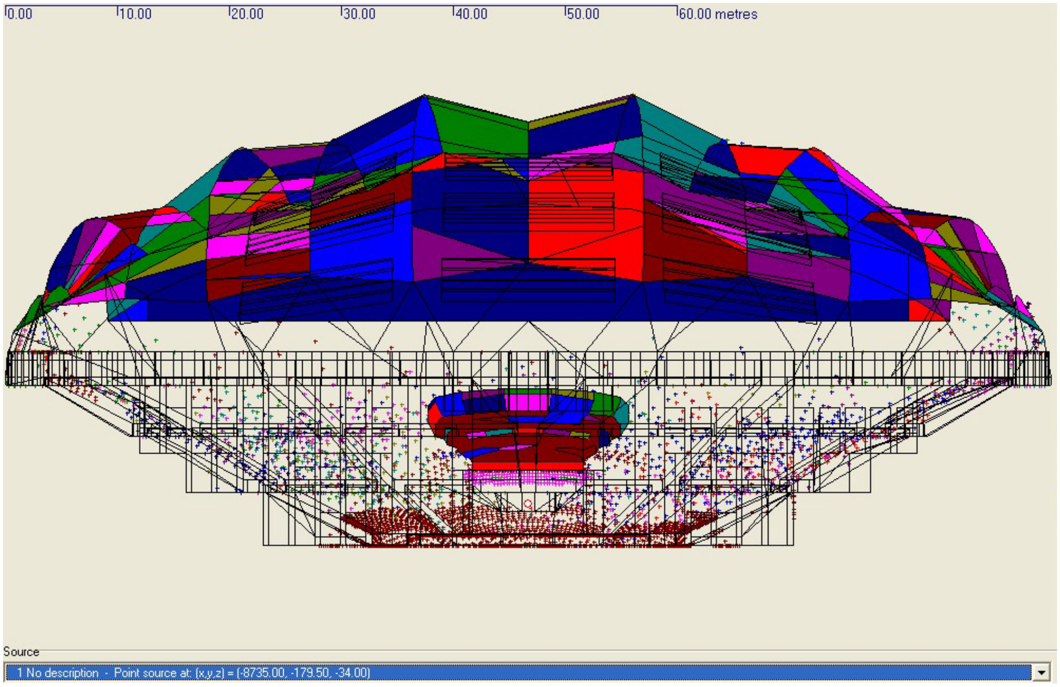


Figure 80. Reflector coverage view 1.

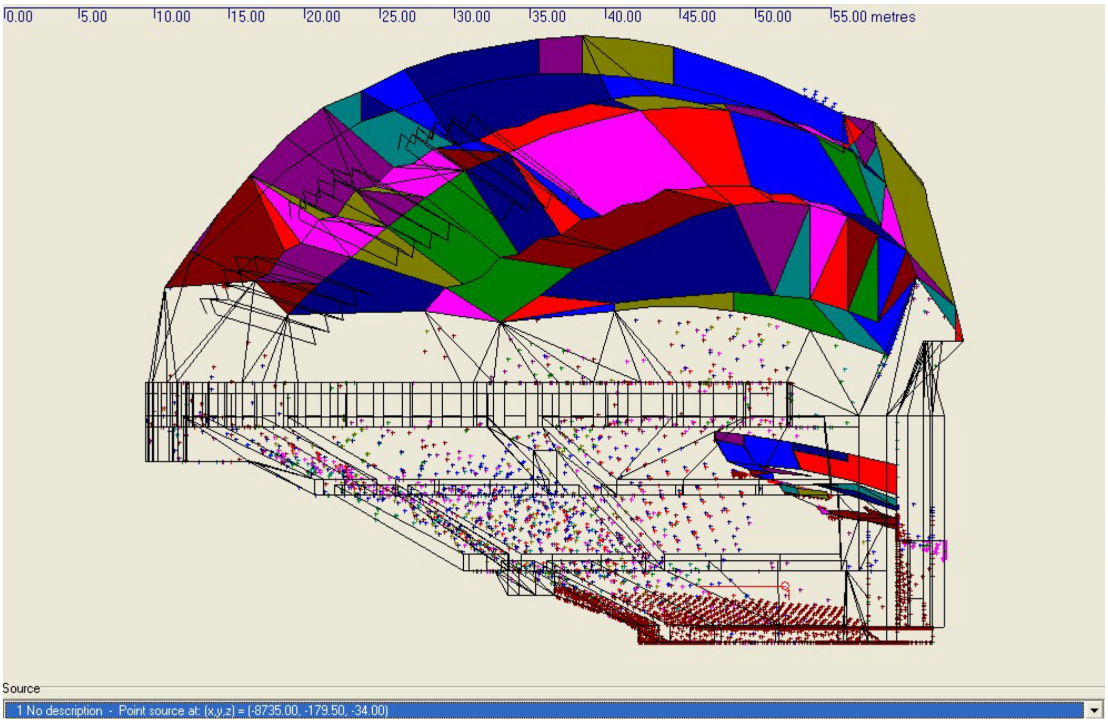


Figure 81. Reflector coverage view 2.

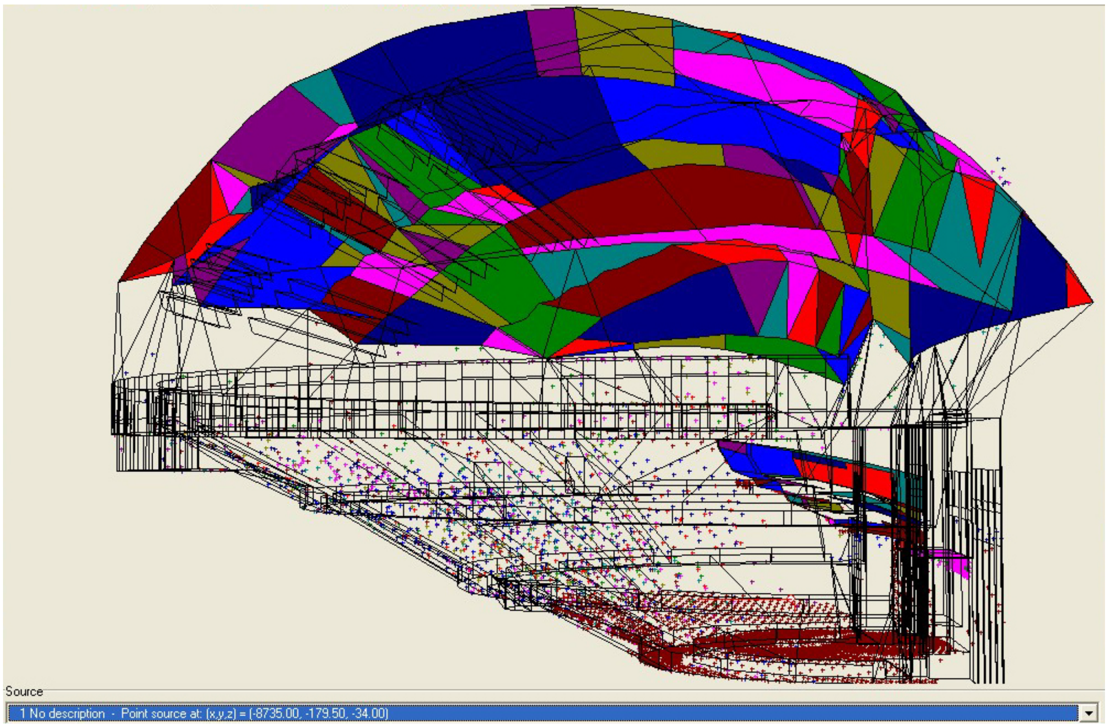


Figure 82. Reflector coverage view 3.

The reflector coverage displays illustrate a similar result as sound pressure level. The sound pressure level is mostly increased by the reflectors adding the energy of the reflected sound to the direct sound. If the sound can not be reflected to the seating areas adequately, the direct sound might be insufficient at the places especially which are far from the stage. The reflector coverage results of ODEON is exemplifying this same thing, at which the sound is mostly reflected to the first tiers followed by the center rows of the mid tiers, whereas the frequency of the dots which can be seen from the figures are decreasing through the upper tiers and becomes very scarce at the sides of the mid and the back tiers. This proves that the reflectors are not designed properly for the sound to be carried all over the seating area equally and sufficiently. This is also caused by the fan-type plan at which the area is increasing through the back seats and consequently the density of the sound reflected from the diffusers is lessened.

5.3.8. Analysis of the Results

As the analysis of the results, the fully-occupied hall is evaluated from the simulations. The causes for the problems and the relations with the subjective measures of this objective parameters for the hall are assessed.

Reverberation Time (RT); from the maps and the graphs it is found that the results are much higher than the optimum values for a multi-purpose hall, which causes too much a reverberance, liveness and brilliance subjectively. As the reverberation and reflected sound energy are too strong, the subjectively experienced quality of sound is suffered. These too much reverberance is first of all not acceptable for speech activities. Moreover, for music perception RT rise in bass is important considering the subjective effect of warmth. However both from the real-size and simulation results, it is obviously seen that the low frequency RT is lower than the mid frequency, while this ratio should be higher especially in the large halls like Bilkent ODEON. This cold bass causes the reduction in spatial impression.

Analyzing the maps for the overall condition of the hall considering reverberation, it could be said that the hall is not dynamically responding well with a good uniformity. There are places in the audience area where the sound focuses strongly, besides the dead spots created throughout the hall. Sometimes these problematic places are very closer to each other. These places will change depending on the location of source, in other words the position of the performer or orchestra. As the reverberation time is a parameter that should be almost same throughout the hall, in this case the seats could not be rated for their acoustic quality. Moreover, the echoes are seen in most of the tier groups.

Extensive concave surfaces and the curvatures throughout the hall are the major cause for focusing at audience positions. Besides, the excessive volume eases the echo formation and the longer reverberation. If the amphitheater in this sizes are closed than the reverberant sound becomes the disturbing noise. The recommended volume for multipurpose halls is given as 7 m^3/occupant in the Table 6., whereas in the case of Bilkent ODEON this ratio is 22.3 m^3/occupant, which is much higher than the optimum value.

The concave back arcade result in unpleasant focused reflections at seats close to that walls, whereas elsewhere there is a lack of early sound, particularly from the front. The rear wall should reflect back the sound to the stage. However, at this example the rear wall is too far from the stage beside its focusing sound at the audience position by its concave form.

Despite the use of the reflector above the stage there are areas in the back part of the roof, which cause strong late reflections. And these reflections lead to echoes inside the audience area. The large plane surfaces of the roof membrane are another important cause for strong reflections. The concentration of long delayed reflections from the concave roof membrane cause echoes, besides tonal harshness and a loud sound. The ceiling is usually the largest room surface as in the case here. The main concern is to avoid tone coloration effects. If the ceiling reflector is either first or prominent in the reflection sequence, it should preferably be diffused.

In some cases the poor acoustic quality is due to the lack of early reflections and the slow sound decay, which shows too much a reverberation time (Cocchi 77).

The slow sound decay of Bilkent ODEON cause too long a reverberation time which is masked by an earlier louder sound and consequently become inaudible in some seats with low sound pressure levels.

In auditoria the major absorbing surfaces are the clothed audience, who absorb about %90 of incident energy at mid-frequencies. Besides reverberation time, this effect sharply decreases the values of most of the parameters when the hall is considered as fully-occupied however the decrease is still not sufficient for the proper reverberation time conditions at Bilkent ODEON.

Early Decay Time (EDT); from the maps the parameter is not to be found in the acceptable range throughout the hall. Being the subjective interpretation of reverberation time it is more critical in defining the acoustical quality of the ODEON which is sensitive to room geometry. In large halls it is normal for EDT to vary in important amounts due to the remoteness of the surfaces. So different from RT, EDT could be rated for different seating locations of the hall. From the maps it is resulted that the values are better at the front tiers, especially at the central part of the front tiers, whereas they are rising towards the back seats and they are worst at the back sides. These values are due to the late sound rising towards the remote areas which are coming reflected back from surfaces like the ceiling. This late sound increases the values of EDT at the remote locations, whereas the early sound is higher at the areas closer to the stage and makes the parameter smaller.

Another problem is the focuses and the dead points among the hall, which brings the uneven distribution of the sound. Less diffusing concave surfaces is one of the reasons of that uneven distribution of sound. EDT is lower than the RT in general, however for a better quality of acoustics it should be at mid frequencies about 0.5 s longer than RT. Well diffused sound field would make closer the EDT with reverberation time, and acoustically liked by the audience.

Clarity (C80); this is important especially for hearing the musical details. Analyzing the clarity maps for fully-occupied hall, most of the seating area is found to be out of the range for optimum values of clarity. The parameter is found to be best in the front tiers, the central area from front to back is better than the sides and the values are worst in the mid and back tiers decreasing from central area to the sides. The clarity is negative in these back and mid sides, which is especially bad for the speech.

The problem with a large space is maintaining sufficient early reflections when some seats are inevitably remote from useful surfaces. The early sound decreases faster than the late, so in the upper parts the early reflections become much more scarce. These are the main reasons for the bad quality in the parameter at the remote places from the stage. In the case of Bilkent ODEON, the excessive reverberant sound which is higher than the early sound undermines the acoustic clarity and makes the sound blurred. There is no well balanced acoustics due to the uneven distribution of the sound field. In the case of clarity, there are also some dead spots, besides the excessive values in few of the seating locations. After the amphitheatre is closed with a roofing structure, there arise an excessive volume for a multipurpose hall which is thought to be one of the biggest closed or semi-closed auditoriums throughout the world. This extreme volume is increasing the value of the initial time delay gap and decreasing the early reflections in most of the seating locations.

Definition (D50); likewise the clarity, the definition is also related with the higher values of early reflections in an impulse response. Analyzing the maps for definition, the early reflections become too much in the front seats and make the results higher than the accepted. The reflections become scarce at the upper parts and the values decrease to the acceptable range in some areas. This time the values are better at the mid and back tiers, whereas higher than the accepted in the front rows. The sound distribution for definition might be defined as the worst up to now. Although there are acceptable ratios for back and mid tiers, the uneven distribution make the parameter unsatisfactory throughout the hall. A reason for that uneven distribution of the sound is the insufficient amount of diffusing surfaces. For instance, the specular surface of the travertine cladding should be better changed with an unpolished surface of a rough stone, especially for the backstage. But this is quite impossible and not logical considering economical aspects at this stage.

Lateral Fraction (LF); looking at the maps the lateral fraction throughout the hall is found to be lesser than the minimum limit for the parameter, this brings lack of envelopment for the audience subjectively, besides the lack of room response and the sense of spaciousness. The parameter is related with the proportion of the lateral reflections to non-lateral ones. Not surprisingly, the better values are found at the sides of especially front and back tiers. There are also some good areas at the back tiers which are closer to the back arcade, where the proportion of sound arriving at the listener from the adjacent walls are in higher proportions at these locations. On the other hand, the central and mid parts of both front, mid and back tiers are showing poor quality of lateral reflection as there are no significant amount of early reflections reaching to the listener from the side.

The sense of envelopment is generally low in large halls as in the case in here. Similarly, better in reverse-fan shaped halls whereas worst at fan-shaped ones. Both of these are characteristics of Bilkent ODEON, and make it not surprising for the poor values of lateral fraction. Wide fan-shapes and semicircular plans usually do not provide strong, early lateral reflections as the side walls will be located too far apart. So, the music will sound distant and lack fullness of tone. This type of plan is reasonable for minimizing the distance from the source to the audience, however with such a plan the intensity of the direct sound at the side seats drops abruptly due to the directivity of the human voice. In addition, with this type of a plan the audience is deprived of side reflections and the concave beam surrounding the arcade at the back causing echoes.

Sound Pressure Level (SPL); the importance of the parameter is in its even distribution throughout the hall, which should not change more than 10 dB. Looking at the maps and reflector coverage figures, it is found that the sound pressure level or in subjective terms loudness is better especially at mid front seats, whereas the levels decrease in the upper seats and mostly at mid and back sides. High definition or clarity is of little use as the sound is too weak to be heard at proper loudness at these locations. By the way, the intimacy as a subjective attribute is both related with the measured sound level and the optimal distribution of lateral reflections. The hall is remote for the audience rather than intimate considering intimacy. There are some extreme spots where the parameter rises strongly among the hall, which is probably implying the focuses at these points. The acoustical defects caused especially by the concave and reflective roof, and the excessive volume. The intensity of the direct sound decreases with increasing distance from the source to the reception point. The grazing incidence sound attenuation is less here due to the adequate aim of the audience seating approximately of 25°. Attenuation caused by the seated audience is reduced. Actually, a constant slope is less favorable than an increasing ascent of the audience area.

The sound level decreases 6 dB for every doubling of distance. When sound travels long distances outside, it is influenced by wind and temperature effects as well. In an enclosed space, on the other hand, the direct sound decreases in level, which is affected by audience. In practice the direct sound energy at the back of a large concert hall may be only %5 of the total; consequently a good reflected energy design is important. In the case of Bilkent ODEON, the reflectors are not satisfactory to reflect the sound sufficiently all over the hall especially at the back seats and sides, and the direct sound becomes insufficient at these locations. These could be seen from the scarce density of reflection pattern at these points from the reflector coverage results. The high sense of reverberance, on the other hand, which is generally thought desirable, is inadequate compensation for this quiet sound at the remote areas.

Sound Transmission Index (STI); the average of the hall is in the fair class for the parameter. However, it should not be forgotten that the simulation is made regarding the source is an omni-directional source. But, considering the speech activities the directional human voice especially at the mid and high frequencies cause a rapid decrease at sides in compare to the front seats, which makes speech intelligibility worst at the remote sides. The background noise and the reverberation time have highly important effect on the STI values. The excessive values of RT poorly affect the values of STI. By the way, the background noise for Bilkent ODEON is measured with the Brüel&Kjaer Sound Level Meter Type 2230 and found as 36.4 dB, which could be omitted. However, when ambient/audience noise intrudes into the mid frequency ranges in the time of performance, then intelligibility will suffer significantly, especially for listener positions in the upper sections (Vassilantonopoulos, *Ancient Greek* 134).

Rating different tier groups for STI, the front rows especially the central parts and the parts closer to the side walls are to be found the best of the hall. The ratios at the mid rows are better for the sides, and rising towards the upper seating locations the values decrease. The worst part could be defined as the mid back tiers. Actually, the size of the hall is so large, that a performance of speech naturally is insufficient. Besides, the echo and uneven distribution of the sound make clearness of speech week for a good intelligibility.

Rating the hall in total considering all of the parameters listed above, it is found that the best place in acoustical quality is the central front tiers which is followed by the side fronts, whereas the worst is the back side tiers which is followed by the mid sides.

6. ACOUSTICAL RENOVATION OF THE HALL

The echoes and the uneven distribution of the sound are the major acoustic problems of the hall. These are basically caused by the rigid surfaces with very reflective characteristics, and the semi-round space in Bilkent ODEON both of the roof construction and the hall shape. It shouldn't be forgotten that the major surfaces in an auditorium generally has acoustic implications.

According to Cocchi, the goal of the acoustical improvement should be to establish balanced behavior of the auditorium, either for music or for speech (80). Well-distributed sound field should be obtained for Bilkent ODEON. Actually, the measures had to be taken to avoid defects at the design stage, because in the completed hall their elimination is a difficult and sometimes even an impossible task. In the case of Bilkent ODEON, the suggestions are for the improvement of the acoustical quality, as wholly perfect solution is quite impossible with logical economical conditions at this stage.

6.1. Suggestions for Improvements

For large rooms as Bilkent ODEON, which are often used for 'multi-purpose' use, it is essential to provide reliable, high-quality sound systems for the reinforcement of speech and certain kinds of musical performance. But these electronic measures are out of the context of this study, which is involving the natural acoustical design parameters and precautions. Besides, as Bilkent ODEON is not a closed place, some environmental factors such as wind, rain etc. are eliminating some precautions to be taken acoustically. The remaining reasonable acoustical renovations to be suggested are discussed in four different groups. The related drawings of the renovated hall are given in Figure 83., Figure 84., Figure 85. and Figure 86.

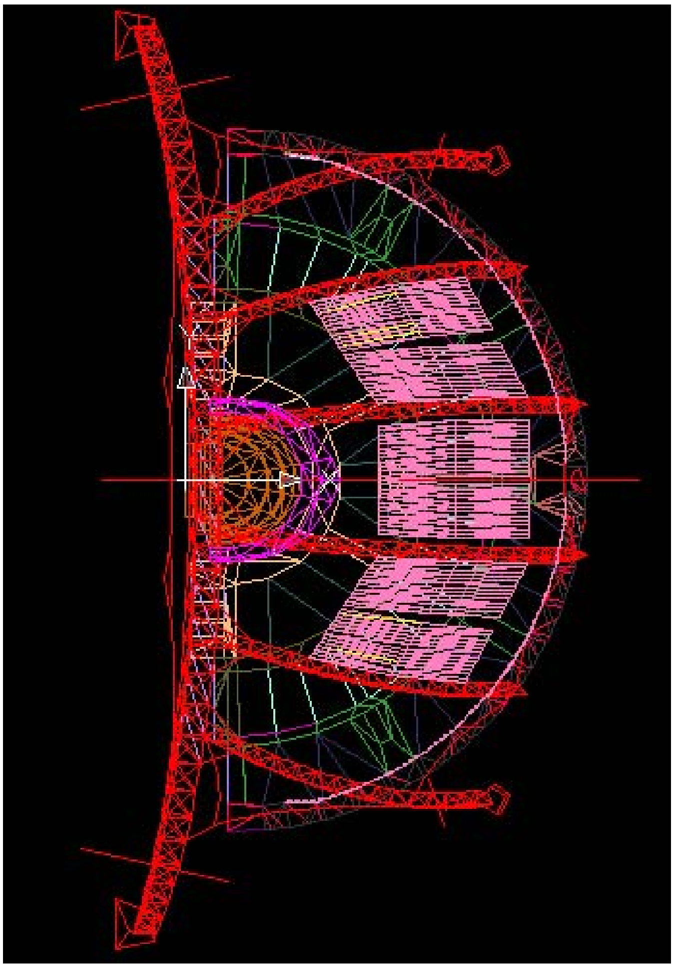


Figure 83. Plan view for the renovated hall.

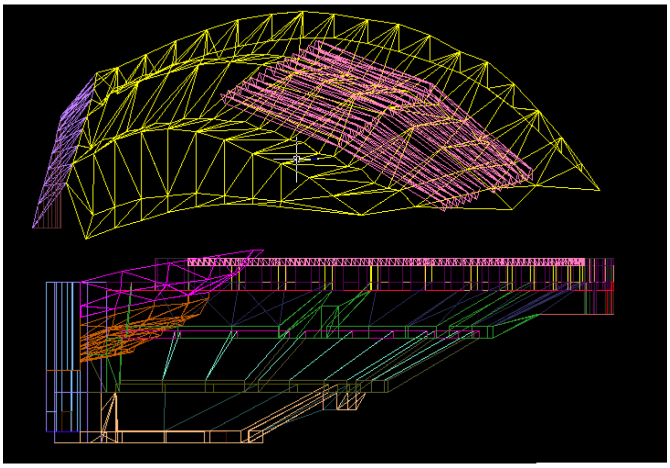


Figure 84. Side view for the renovated hall.

1. Reorienting the fabrics hanged on acoustical bridges; the primary defects including sound foci and uneven distribution of sound are basically caused by the rigid roof membrane and its shape. The previous precaution against the reshaping of the membrane includes hanging more absorbent materials underneath. However, the sound absorption properties and the orientations of the fabrics are not satisfactory for the acoustic correction of the hall.

The roof construction is slightly convex in the cross section, whereas it is closing to a perfect arc in the longitudinal section. The present acoustical fabrics are hanged on parallel to this convex section, whereas the problematic section that causes sound focuses is the opposite one. In this study the first suggestion accordingly is hanging these absorption fabrics parallel to the concave section, as the concave surfaces focus sound, and are also poor distributors of sound energy. The uneven distribution of sound in Bilkent ODEON is aimed to be improved by this way. The new orientation of the acoustical bridges could be seen from Figure 83. and Figure 84.

2. Changing the fabric with a nonwoven; concave surfaces which focus sound on or near the audience are taboo for auditoria for which the treatment is difficult in completed buildings. For example, absorbent materials may still reflect enough that causes problems. For the acoustical bridges to become more efficient especially for decreasing the excessive reverberation time, the fabrics are suggested to be replaced by nonwoven fabrics, which have much higher values of sound absorption.

In order to give basic information about the nonwovens that are used in the renovation of the hall, they could be defined as sheet or web structures bonded together by entangling fiber or filaments mechanically, thermally or chemically. They are flat, porous sheets that are made directly from separate fibers or from molten plastic or plastic film, which are not made by weaving or knitting and do not require converting the fibers to yarn ("About Nonwovens").

The basic advantage of the material is the high sound absorption values. The acoustic energy is converted into heat, principally by viscous friction between the vibrating particles of the sound-emitting medium and the structure of this porous material. Nonwoven fabrics are engineered fabrics that are much durable and with a higher maintenance than a woven fabric, which can also mimic the appearance and texture of it. Besides, the low material thickness of 0.2 mm, strength, stretch, resilience, reduced risk of condensation water forming as the intentional omission of an insulating effect supports continuous air exchange, are the other advantages for it to be applied for Bilkent ODEON. And finally, it also achieves good balance between product use-life and cost ("Technical Nonwovens").

The brand of the nonwoven used in the simulation as an input data for the sound absorption coefficients is Nomex-nonwovens Style-CIC006. The sound absorption coefficients of the material are given in the Table 16. Some other technical properties of the material are given as;

Noise Reduction Coefficient (NRC): 0.25

Thermal Conductivity: 0.315 (W/m.K)

Thermal Resistance: 7.90 (m.K/W) (“High Performance”).

3. Extending the over-stage canopy; the designer should concern with getting reflections to the most distant seats with the aid of the reflectors above the stage, not only to the front of the stage. In a space as large as this it is expected a quieter sound at seats remote from the walls. The uniformity and the minor risks of low sound levels could be obtained by the careful orientation of the stage reflectors.

Analysis of the Bilkent ODEON proves that, the central front seats are rated as best throughout the hall, whereas the back seats especially the side backs are worst among the others. Looking at the maps of different parameters the zone of better acoustical quality in the central front is clearly selected. The perimeters of this circular zone are mostly due to the dimension and orientation of the over-stage canopy. Extending this over-stage canopy through sideward and forward, as the limits of the backstage permits, the zone of better acoustical quality is supposed to be expanded. The renovated canopy is shown in the Figure 85. The brown colored lines are implying the present condition of the canopy whereas the pink lines are showing the suggested extension for the canopy.

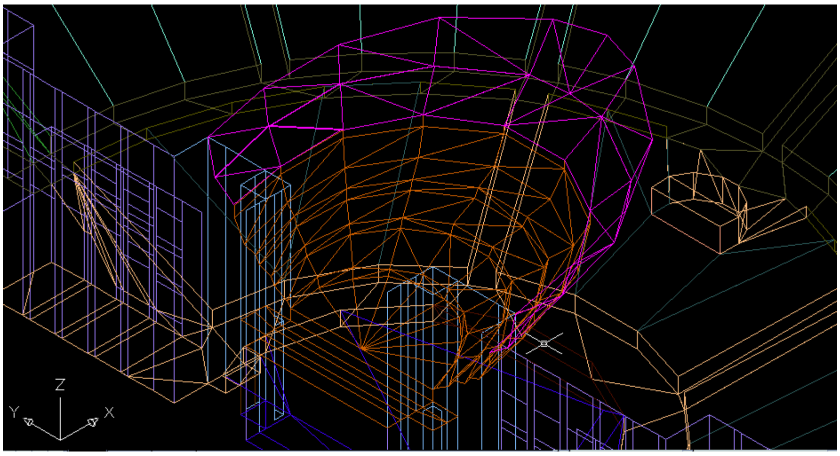


Figure 85. The axonometric view for the renovated canopy.

4. Fragmenting the semi-circular beam of the back arcade; diffusing wall surfaces are important for the good distribution of sound among the hall. The concave surfaces cause focusing and echoes as mentioned before. The back arcade is one of these concave surfaces. The suggestion for the arcade is principally breaking up the front beam into smaller scattering surfaces, than the geometrically focused reflection will turn into a diffuse reflection.

The diffused pattern could be formed by the material called glass-fibre reinforced concrete, which is a mixture of cement, fine aggregate, water and chemical admixtures. This is an environmentally friendly composite, with its low consumption of energy and natural raw materials, and could be formed into a great variety of products with its flexible ability to meet performance, appearance and cost parameters. The glass-fibre reinforced concrete (GRC) is much absorbent than the normal concrete, and different mixtures is mostly used in the outdoor facades as it is durable against water, for giving variable motifs to the exteriors ("What is GRC?"). These properties of the material to be molded into desired shape, durability and wide use in outdoor spaces, besides its reasonable absorption with its fiber component make it a proper material for fragmenting the back arcade. The surfaces of the material could also be given different textures, which is especially important in the case of Bilkent ODEON, as with the textures on the concrete the scattering and accordingly the diffusivity could be increased.

The concave beam is fragmented by every 1 m portion, and each element of GRC with a width of 1 m, length of 0.75 m, depth of 0.01 m at the bottom and 0.02 m at the top, with an inclination towards the audience about 8° is anchored to the beam by a steel frame carcass at the back of the GRC. This fragmentation of the beam could be observed in detail from Figure 86. and Figure 87.

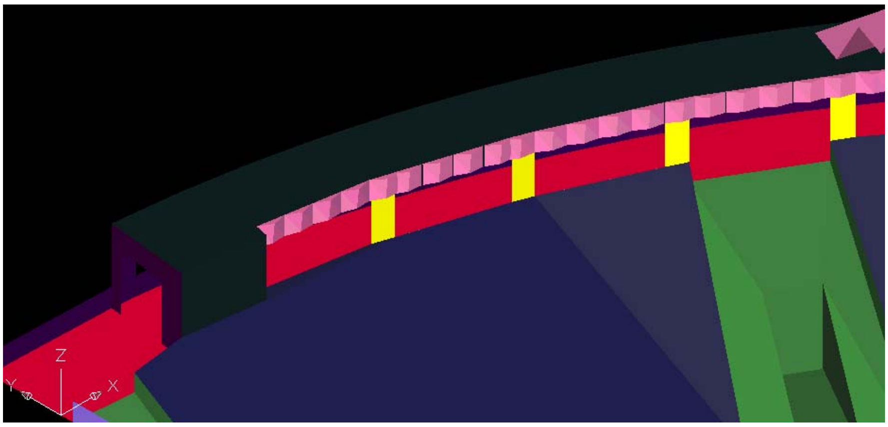


Figure 86. Partial axonometric view of the fragmented beam.

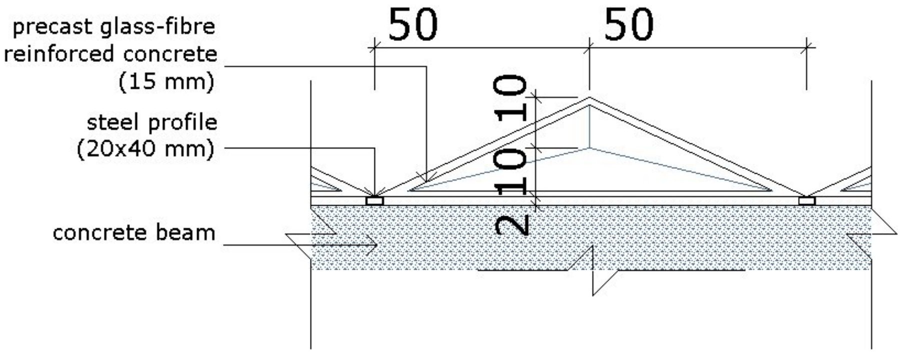


Figure 87. Partial plan view from the fragmented beam surface.

6.2. Simulation of the Acoustical Correction

The suggested issues explained above is applied to the model of Bilkent ODEON and the model is simulated at the ODEON Room Acoustics Program Version 6.01 Combined Addition, in order to see the effects of the suggestions on the hall. The Figure 88. and Figure 99. are the views from different locations of the renovated hall as a 3d color display. The differences of emphasized elements could easily be seen from these displays when compared to the previous simulation of present condition.

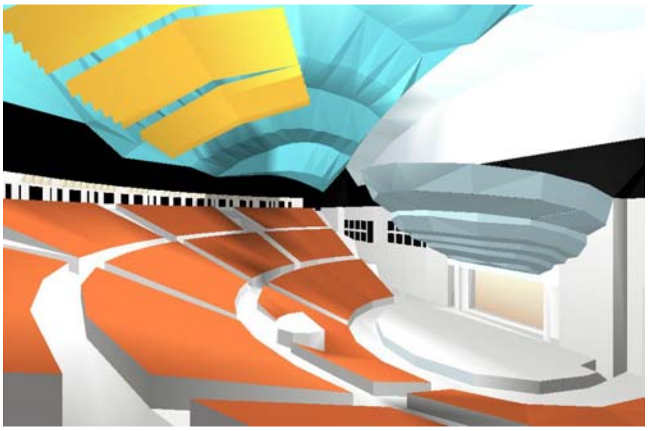


Figure 88. 3d color display of renovated hall view 4.

Figure 89. 3d color display of renovated hall view 5.

The calculation and room parameters are kept same with the previous simulation of the present condition given in Chapter 5.3. The source and receiver positions, defined grid surfaces are not changed. Only the overall gain for the source is given as 31 dB, in order to evaluate the strength parameter. By the way, the color scheme of the distribution maps are changed according to this new version of ODEON, however the importance is in the range of numerical values given in the legend, which are same for both.

Coming to the material assignments, the hall is assumed to be fully-occupied as in the simulation given in Chapter 5.3. There are two materials different from the previous one. One of which is the nonwoven fabric, which is replaced by the present woven fabric. There are many types of nonwovens with varying sound absorption coefficients. A minimum is chosen for the reliability to be applied in the simulation. The other is GRC, which is approximated to the porous concrete, considering that the surface of the GRC is left coarse. The sound absorption coefficients that are used for these two materials are given in the Table 16.

Material Number	Material Specification							
103	Porous concrete blocks without surface finish (Approximated for the GRC) (Christensen).							
Scattering Factor	0,20							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Material Number	**Material Specification**							
123462	Nonwoven fabric ("High Performance").							
Scattering Factor	0,10							
Sound Absorption Coefficients (Hz)	63	125	250	500	1000	2000	4000	8000
	0,07	0,08	0,09	0,18	0,35	0,54	0,75	0,90

Table 16. Sound absorption coefficients for new materials used in the renovated hall.

The first calculation, which shows a significant difference with the previous simulation to be given is the material overview for the renovated hall when it is fully-occupied. This is obtained from the quick estimation calculations of the model.

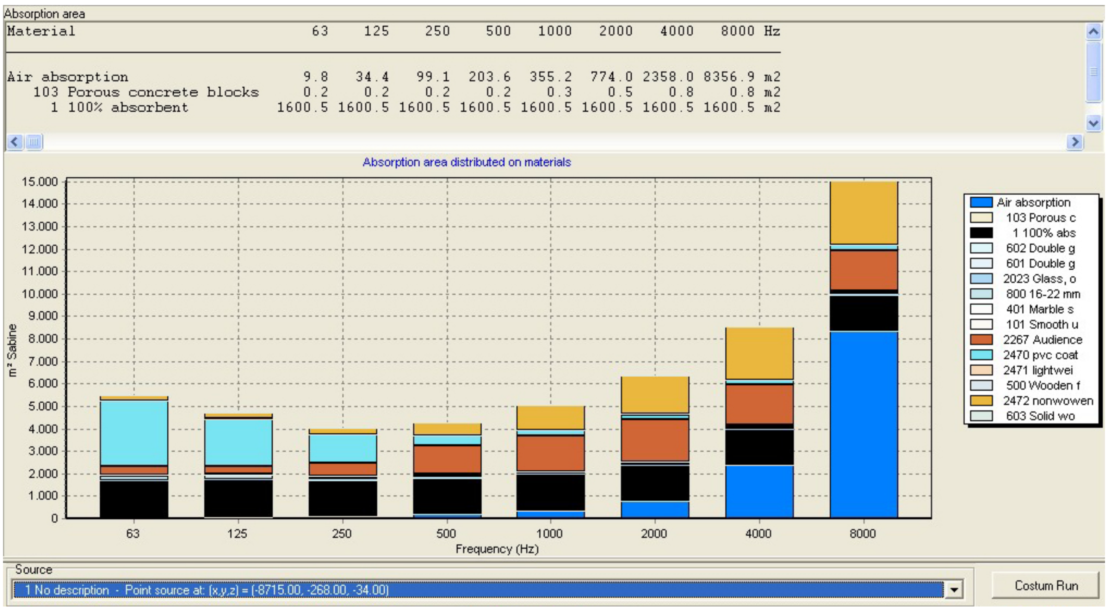


Figure 90. Material overview for the renovated hall.

The material overview is obtained from the quick estimation calculations. The Figure 90. is emphasizing the importance of the fabric change. From the material overview graphs of the previous simulation it is found that the absorption fabric shows a reflective character rather than an absorptive one. The nonwoven fabric, on the other hand, is fulfilling the adequate absorption as seen from the graph. The absorption is increasing at the higher frequencies and become even higher than the audience absorption, which is important considering some acoustical defects as echoes for these higher frequencies.

The next calculation is the global estimation, under which the energy curves, estimated reverberation times and the free path distribution graphs are displayed. These are given in the Figure 91., Figure 92. and Figure 93.

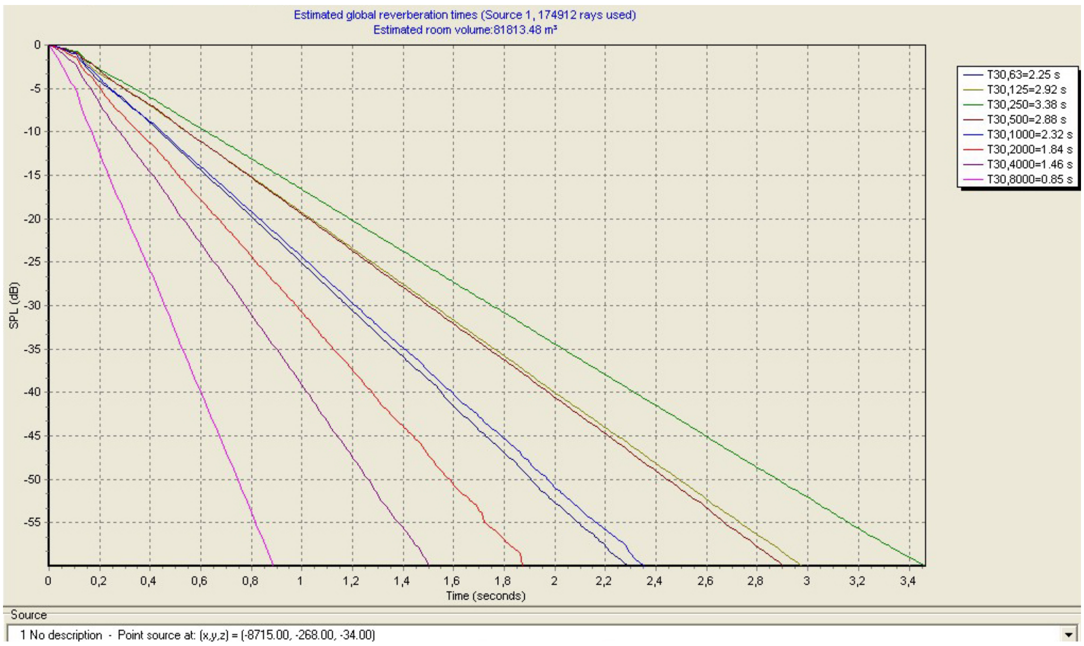


Figure 91. Energy curves for the renovated hall.

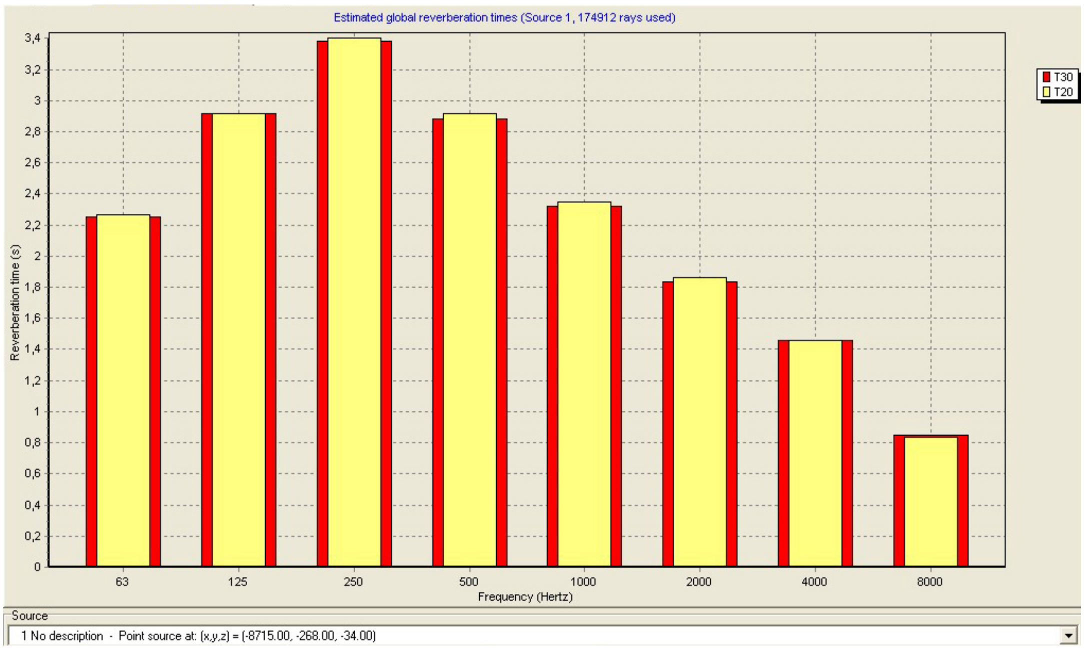


Figure 92. Estimated reverberation times of global estimate for the renovated hall.

The reverberation times for different frequencies are collected from the global estimation calculations given in Figure 91. and Figure 92. The first improvement is in the mid frequency reverberation time that has priority in the assessment of the parameter. The mid frequency reverberation time for the renovated hall, when the hall is in use, is 2.60 s whereas it is 3.05 s in the hall with its present condition. The parameter is still some higher than the upper limits for the concert use but acceptable for liturgical music, however there is a significant decrease of 15% which is quite a noticeable improvement for such a hall. The second issue is the improvement in the warmth or bass ratio of the hall, which is one of the discussed subjective criteria for music use. The bass ratio, which is the average RT at 125 and 250 Hz divided by RT at mid frequencies, is 1.13 for the present hall and 1.21 for the renovated hall. As the lower limit is 1.2 for music performances, the renovated hall is satisfying the criteria.

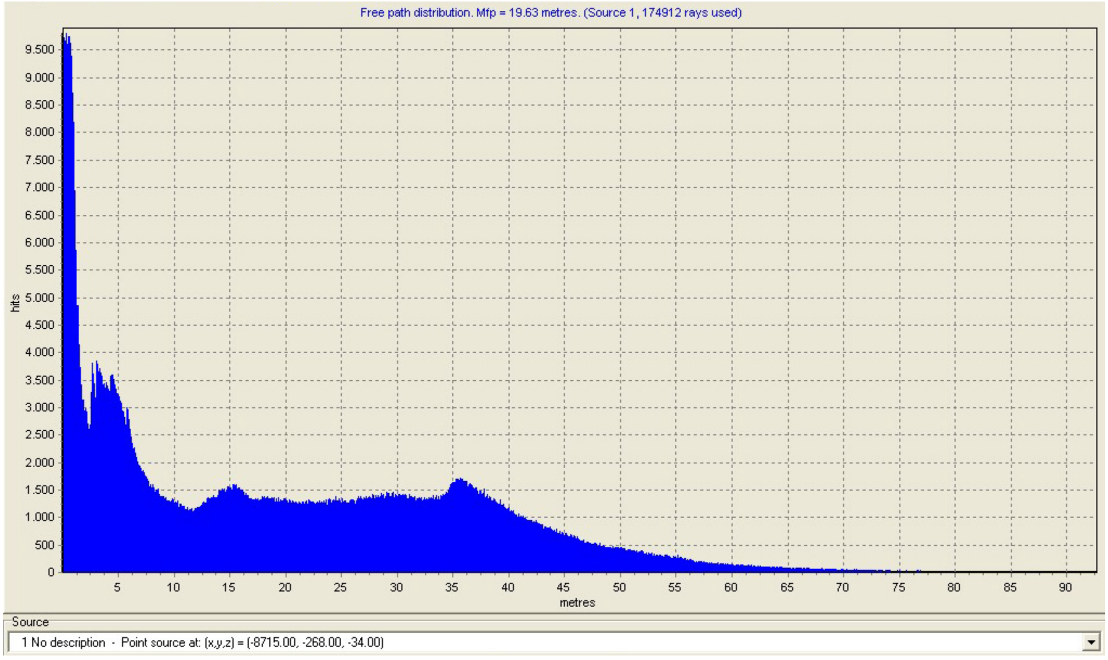


Figure 93. Free path distribution graph for the renovated hall.

Another result of the global estimation calculations is the free path distribution graph, as can be observed from the Figure 93. When the renovated hall is compared with the present hall for occupied conditions, it is observed that the jumps in the first five meters are minimized and the decay becomes softer at the renovated hall. This implies an improvement in the distribution of the sound field.

The following results are the grid response calculations for the selected receiver surfaces. The maps are including different parameters, which are improved by the renovated model evaluated for 500 and 1000 Hz. These are including reverberation time (T30), early decay time (EDT), clarity (C80), definition (D50), lateral fraction (LF), sound pressure level distribution (SPL) and sound transmission index (STI).

6.2.1. Reverberation Time (T30) Distribution Maps and Graphs

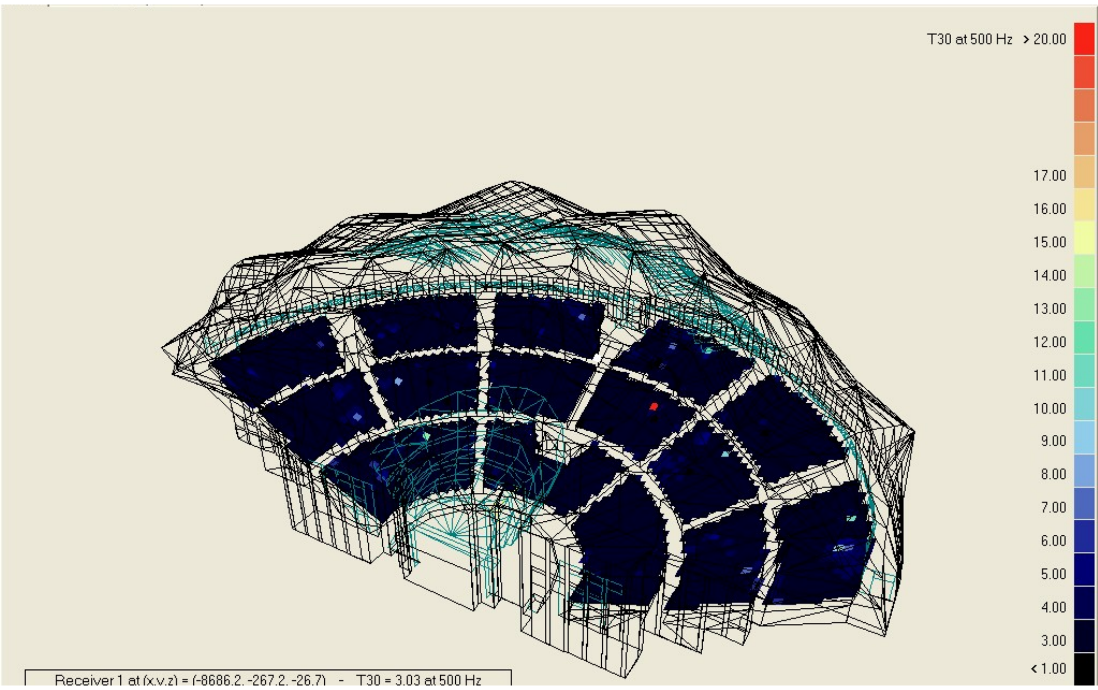


Figure 94. Reverberation time distribution map for 500 Hz and for the renovated hall.

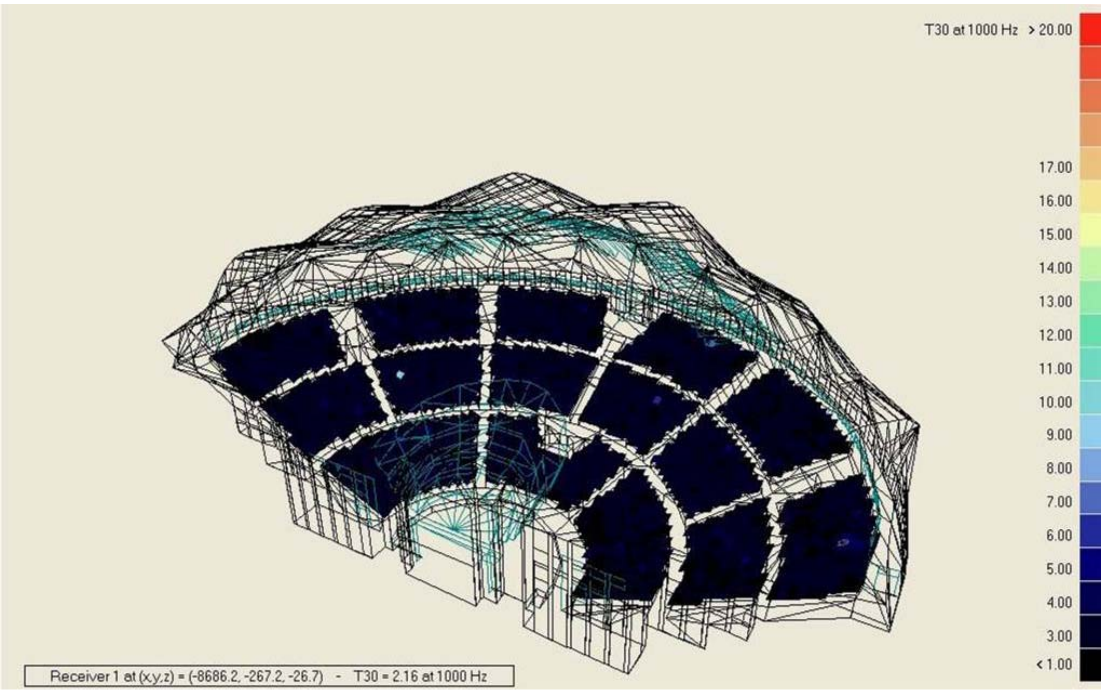


Figure 95. Reverberation time distribution map for 1000 Hz and for the renovated hall.

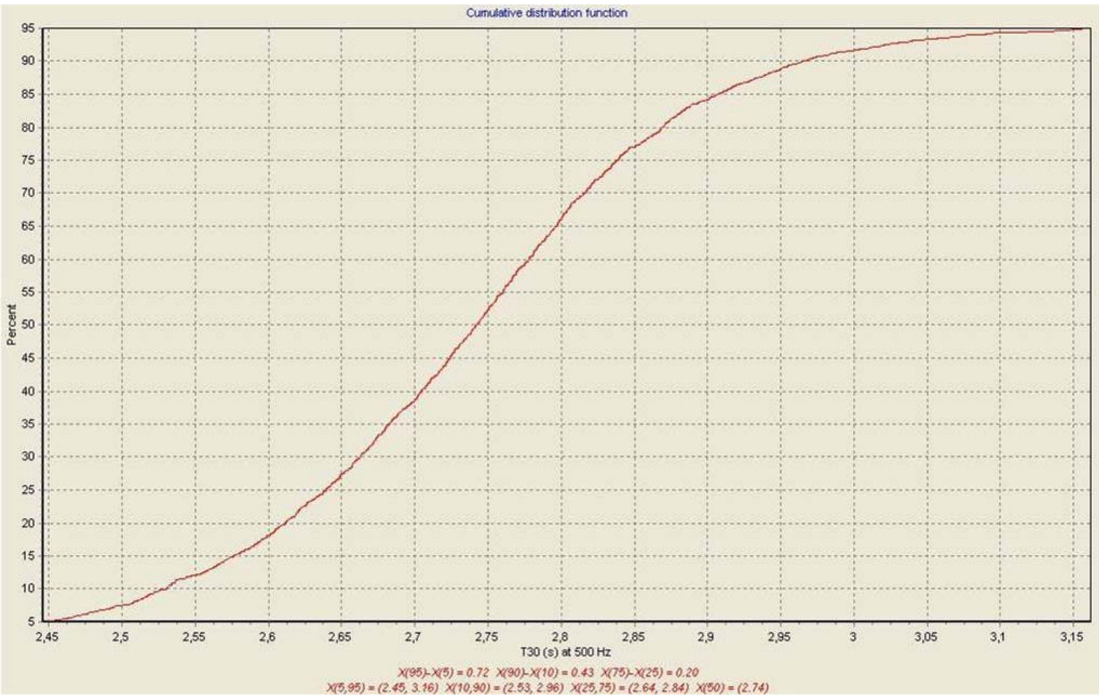


Figure 96. Reverberation time distribution graph for 500 Hz and for the renovated hall.

Figure 97. Reverberation time cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.2. Early Decay Time (EDT) Distribution Maps and Graphs

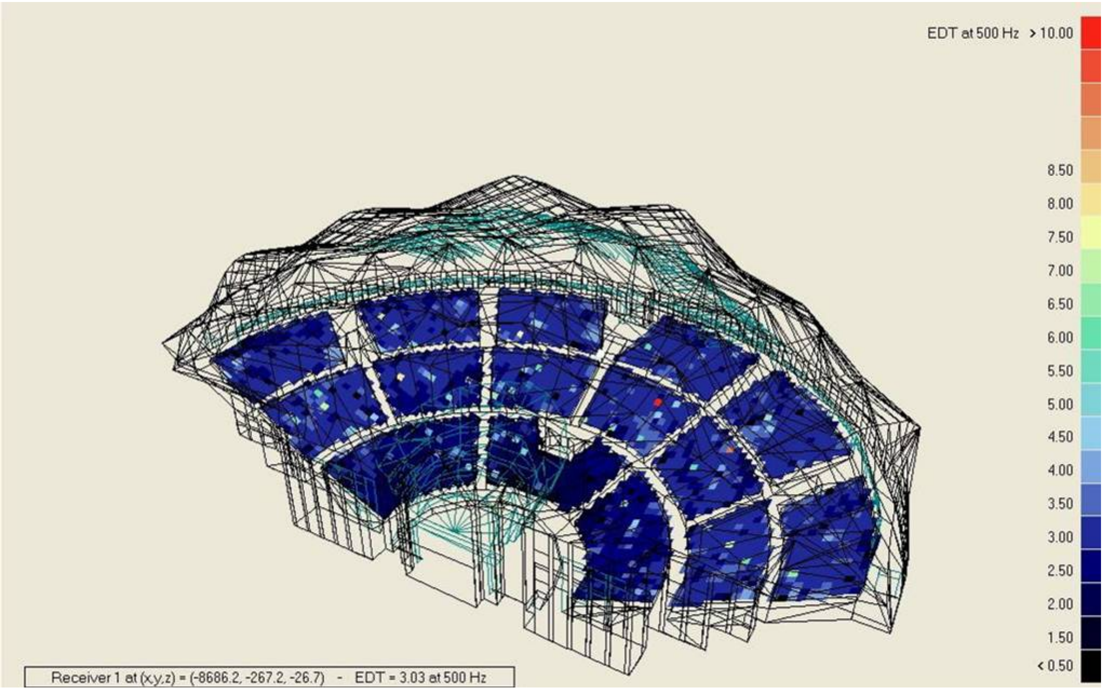


Figure 98. Early decay time distribution map for 500 Hz and for the renovated hall.

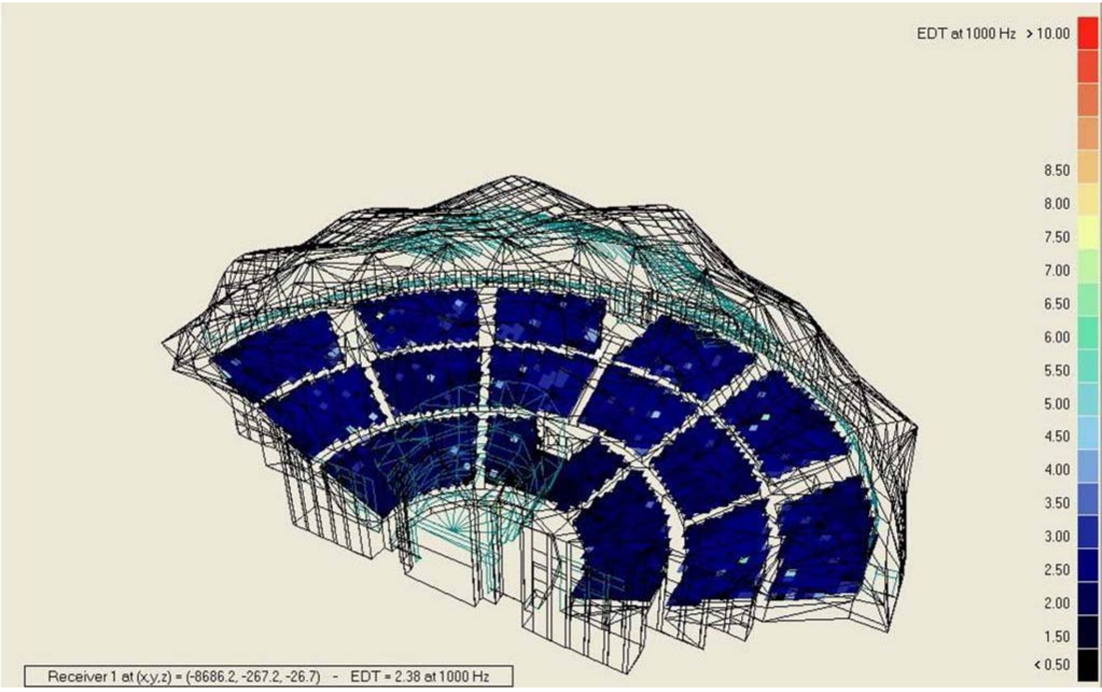


Figure 99. Early decay time distribution map for 1000 Hz and for the renovated hall.

Figure 100. Early decay time cumulative distribution graph for 500 Hz and for the renovated hall.

Figure 101. Early decay time cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.3. Clarity (C80) Distribution Maps and Graphs

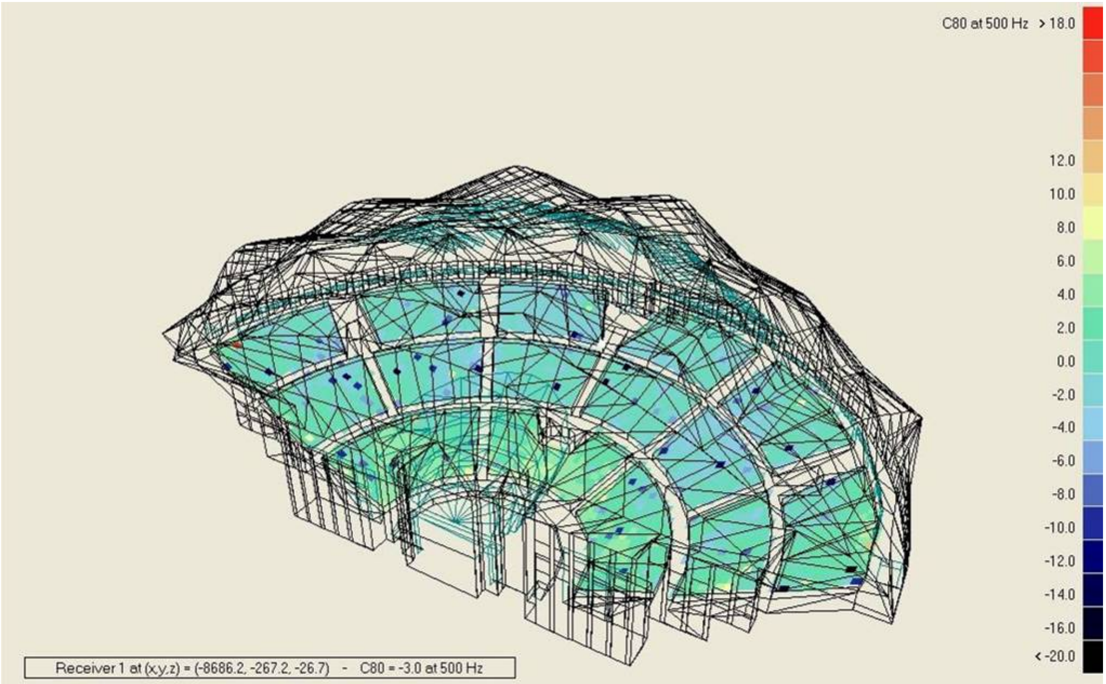


Figure 102. Clarity distribution map for 500 Hz and for the renovated hall.

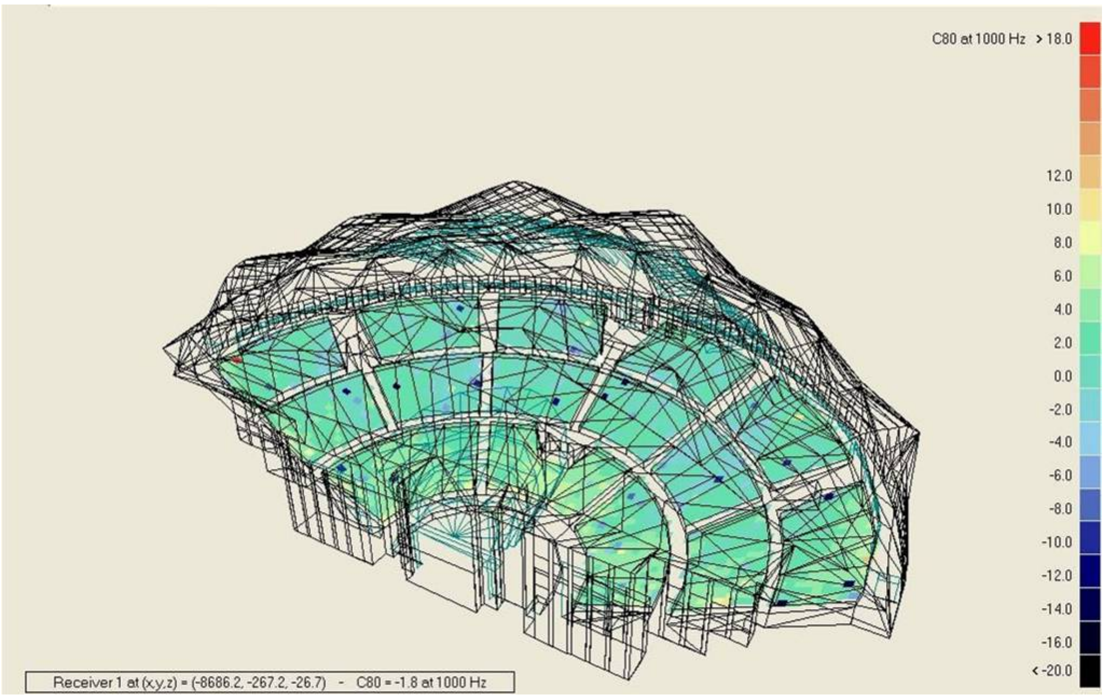


Figure 103. Clarity distribution map for 1000 Hz and for the renovated hall.

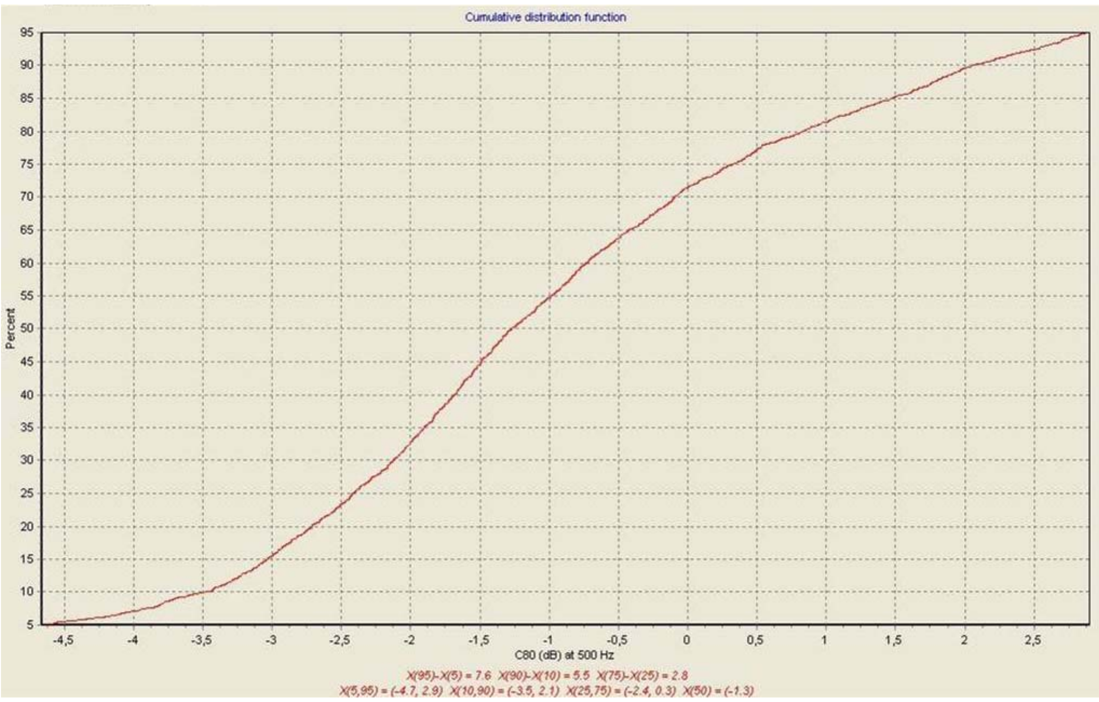


Figure 104. Clarity cumulative distribution graph for 500 Hz and for the renovated hall.

Figure 105. Clarity cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.4. Definition (D50) Distribution Maps and Graphs

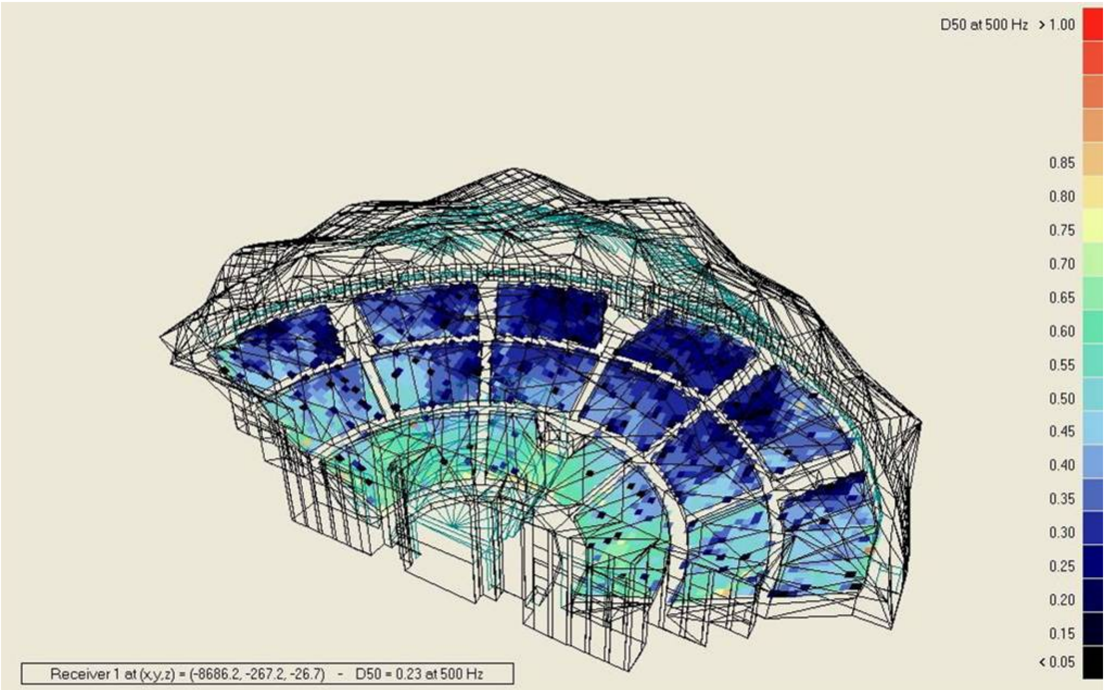


Figure 106. Definition distribution map for 500 Hz and for the renovated hall.

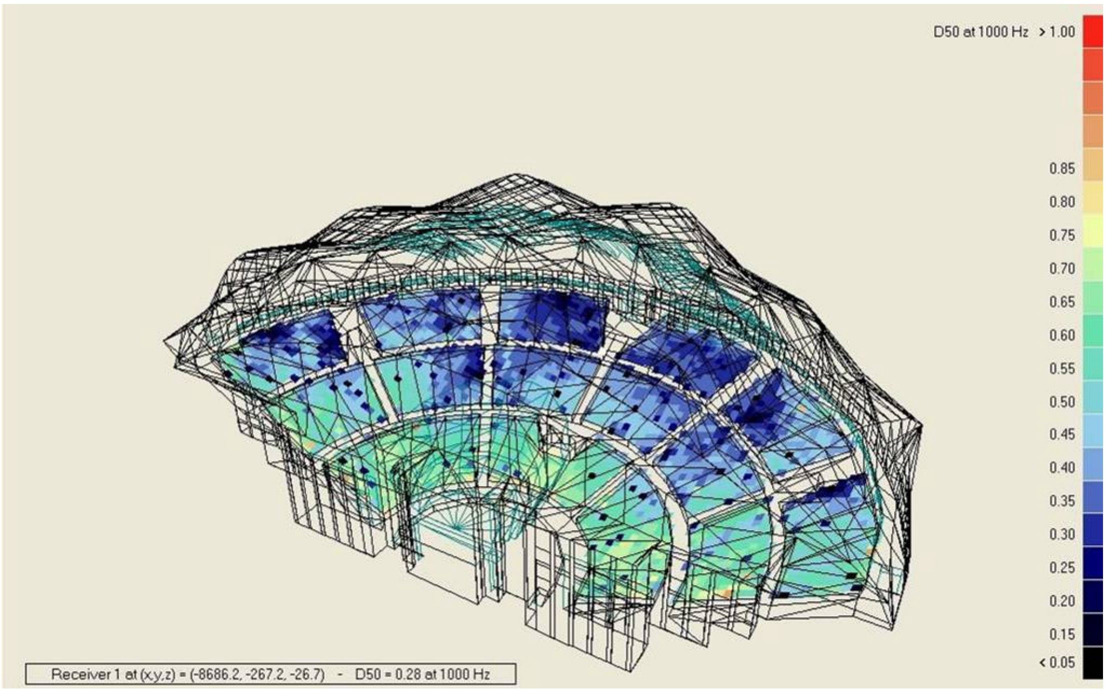


Figure 107. Definition distribution map for 1000 Hz and for the renovated hall.

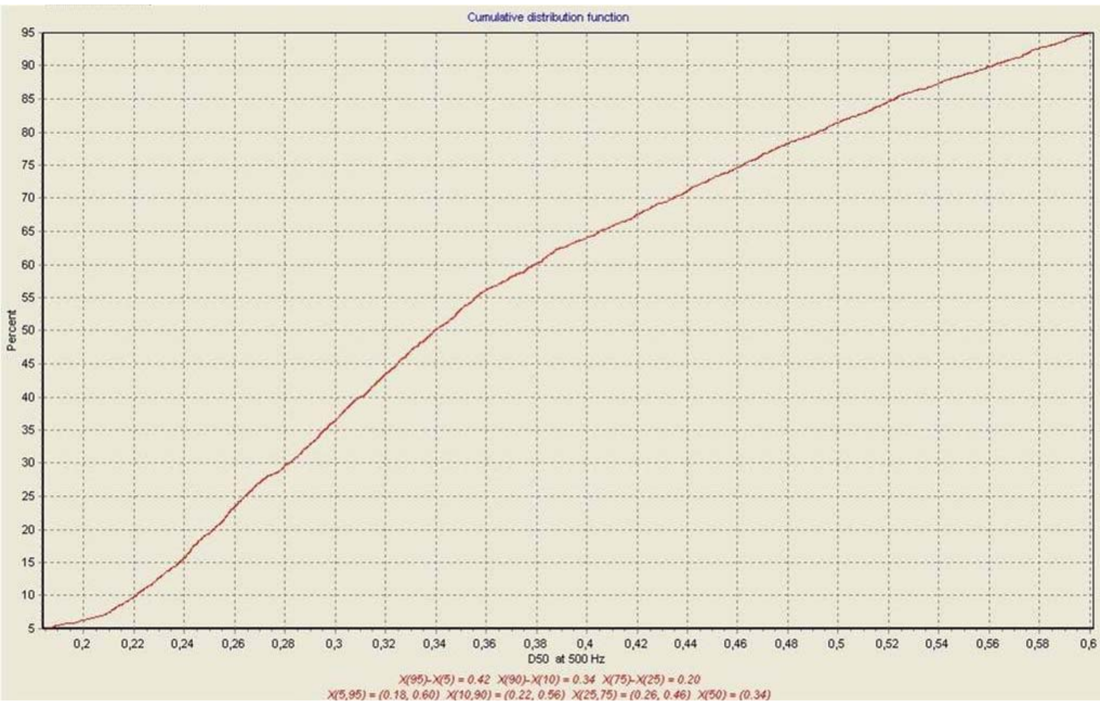


Figure 108. Definition cumulative distribution graph for 500 Hz and for the renovated hall.

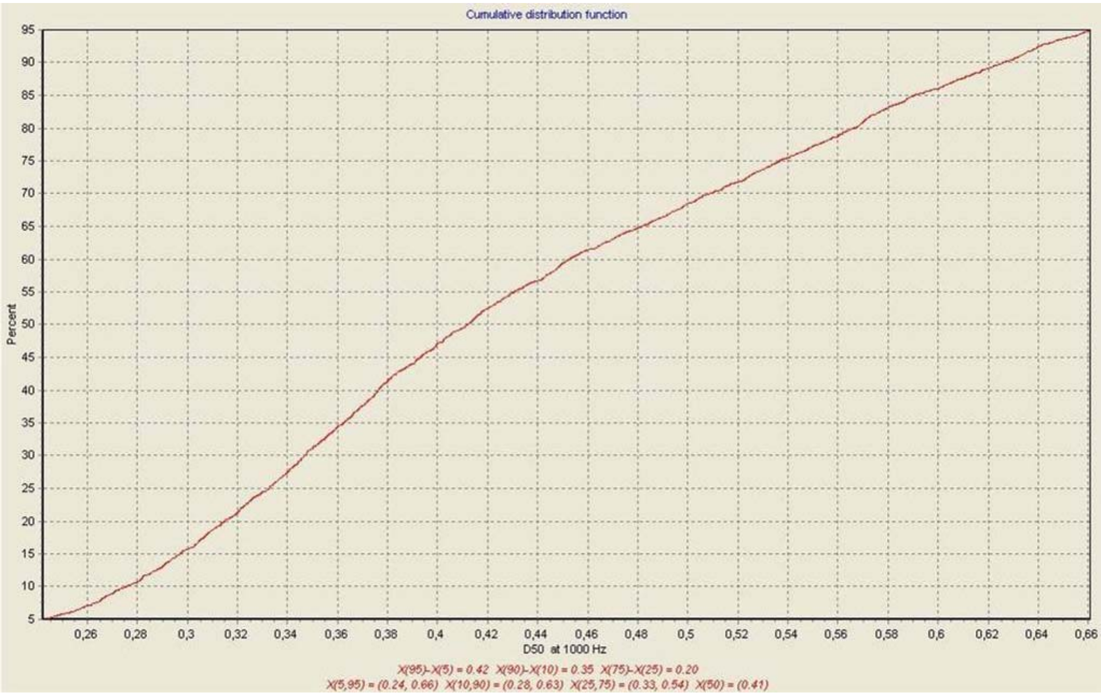


Figure 109. Definition cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.5. Lateral Fraction (LF) Distribution Maps and Graphs

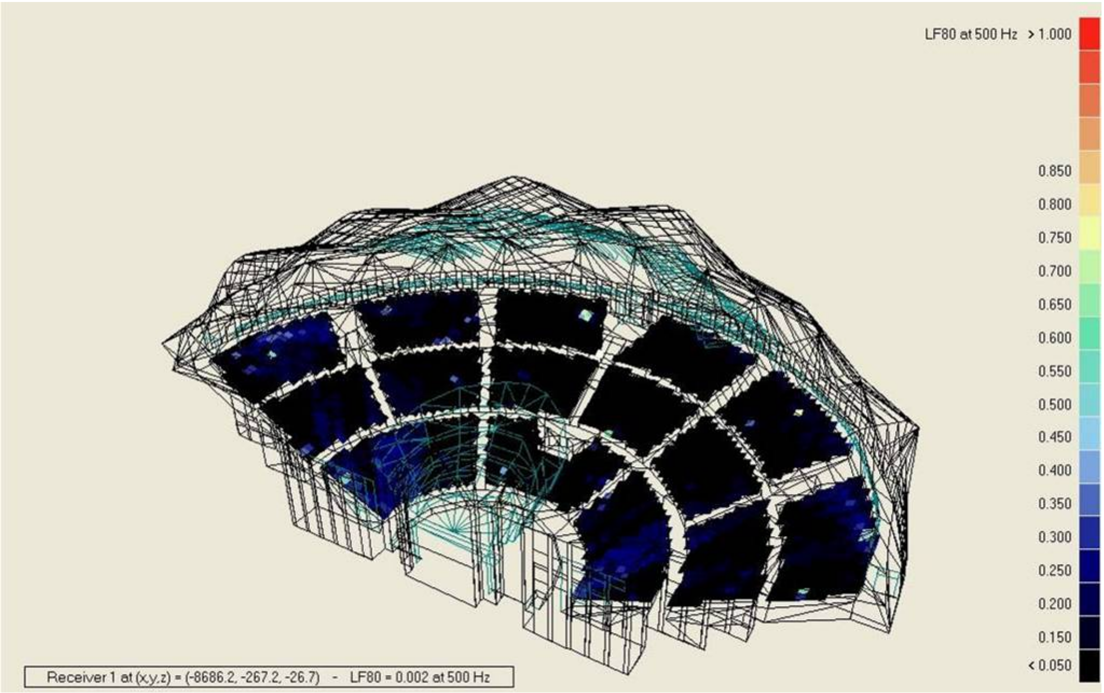


Figure 110. Lateral fraction distribution map for 500 Hz and for the renovated hall.

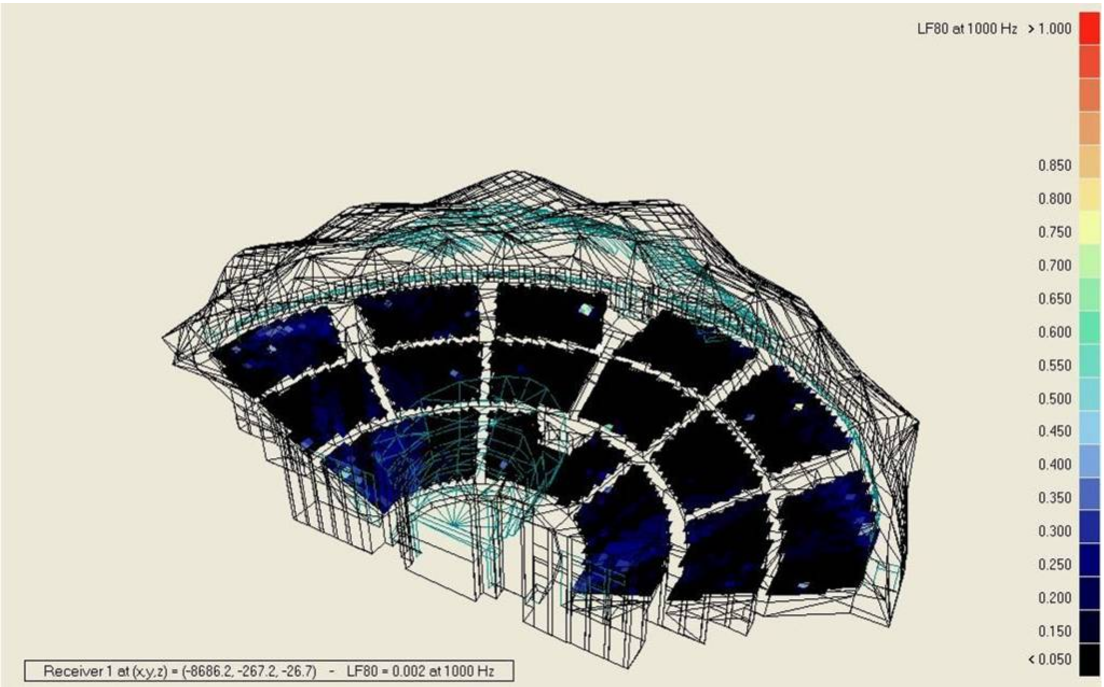


Figure 111. Lateral fraction distribution map for 1000 Hz and for the renovated hall.

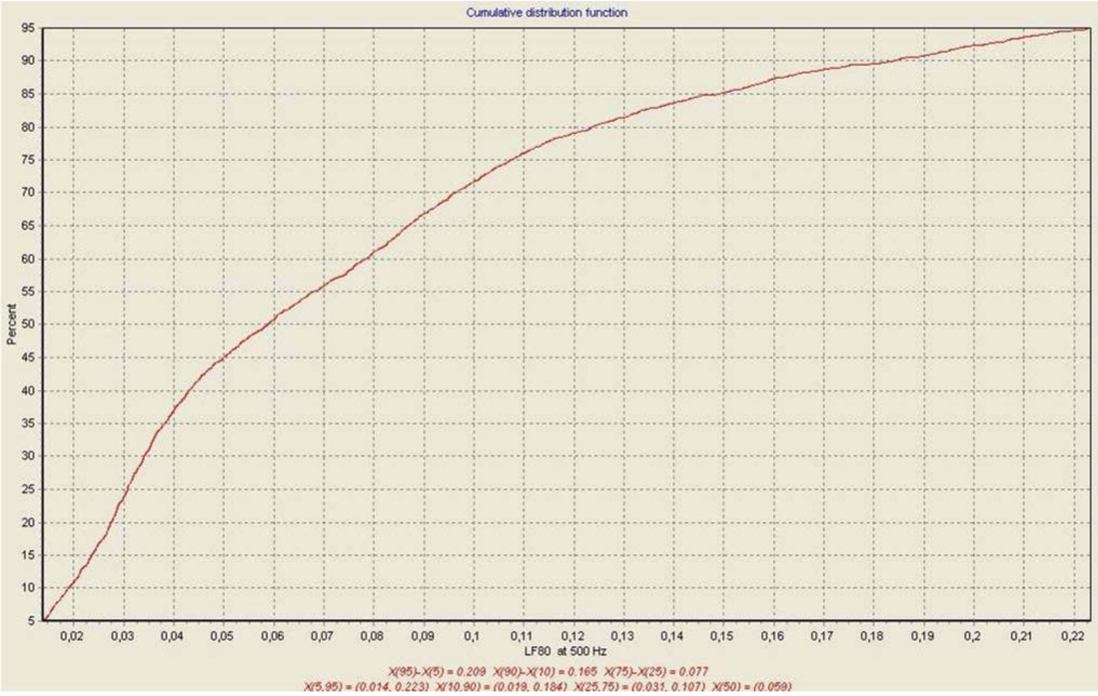


Figure 112. Lateral fraction cumulative distribution graph for 500 Hz and for the renovated hall.

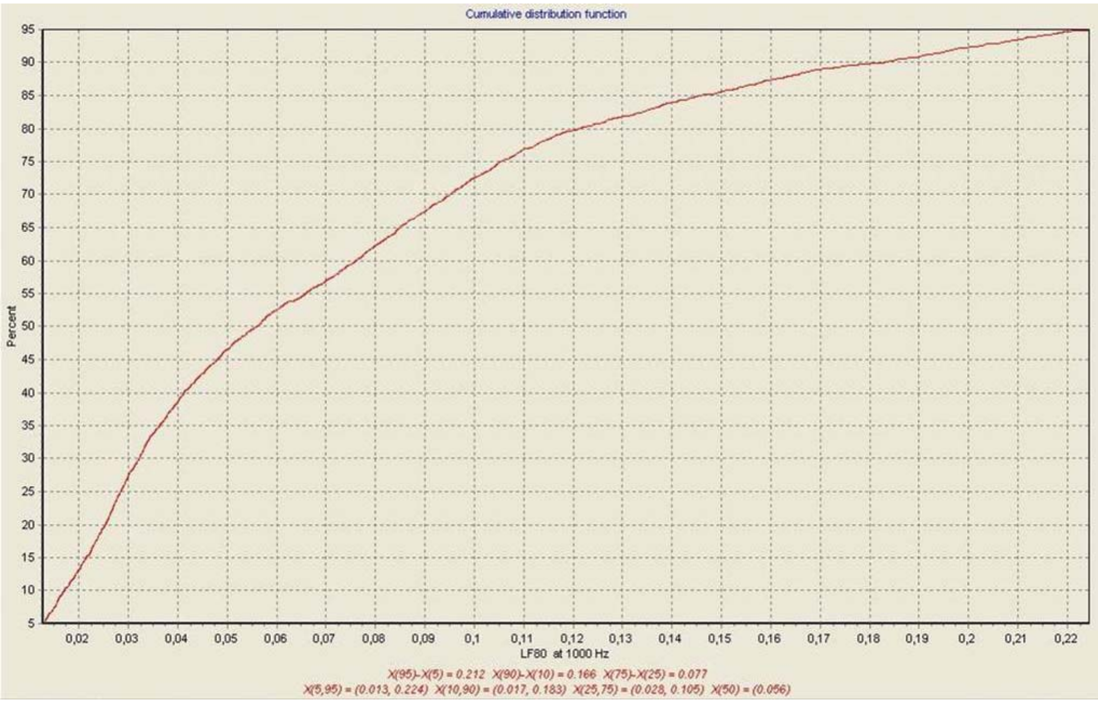


Figure 113. Lateral fraction cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.6. Sound Pressure Level (SPL) Distribution Maps and Graphs

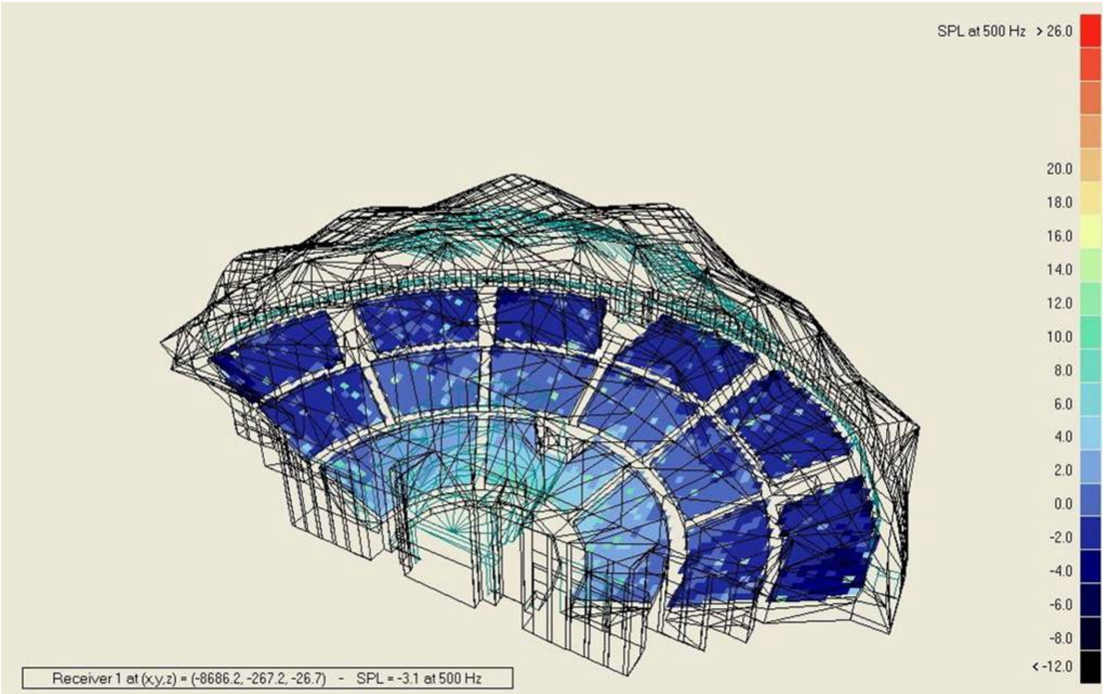


Figure 114. Sound pressure level distribution map for 500 Hz and for the renovated hall.

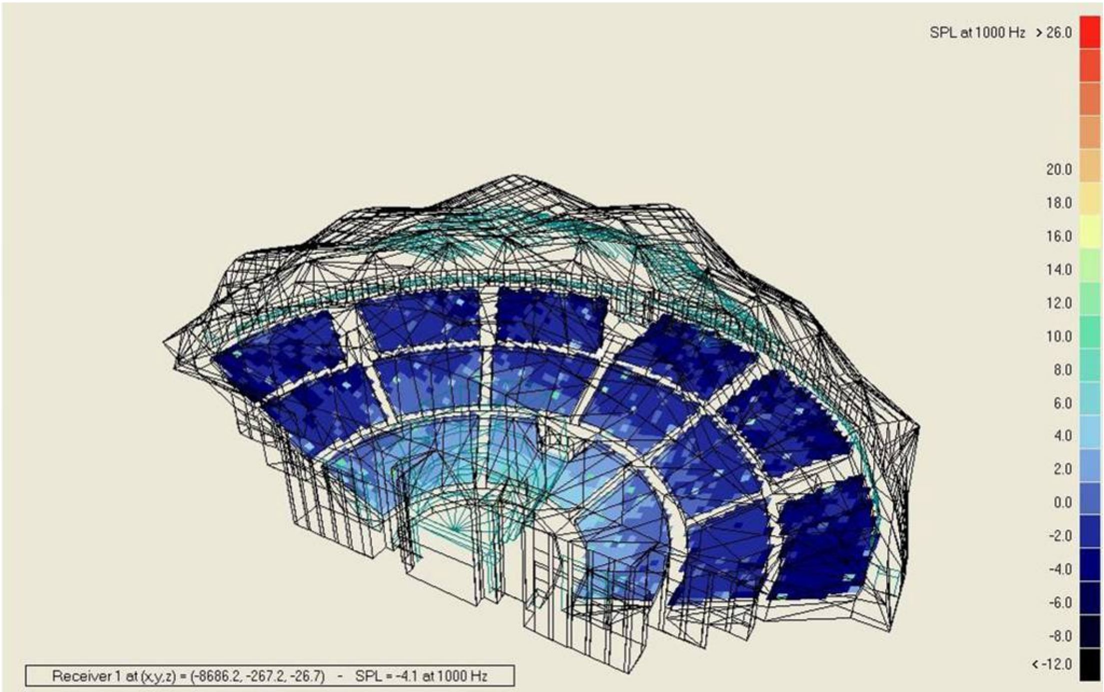


Figure 115. Sound pressure level distribution map for 1000 Hz and for the renovated hall.

Figure 116. Sound pressure level cumulative distribution graph for 500 Hz and for the renovated hall.

Figure 117. Sound pressure level cumulative distribution graph for 1000 Hz and for the renovated hall.

6.2.7. Sound Transmission Index (STI) Distribution Maps and Graphs

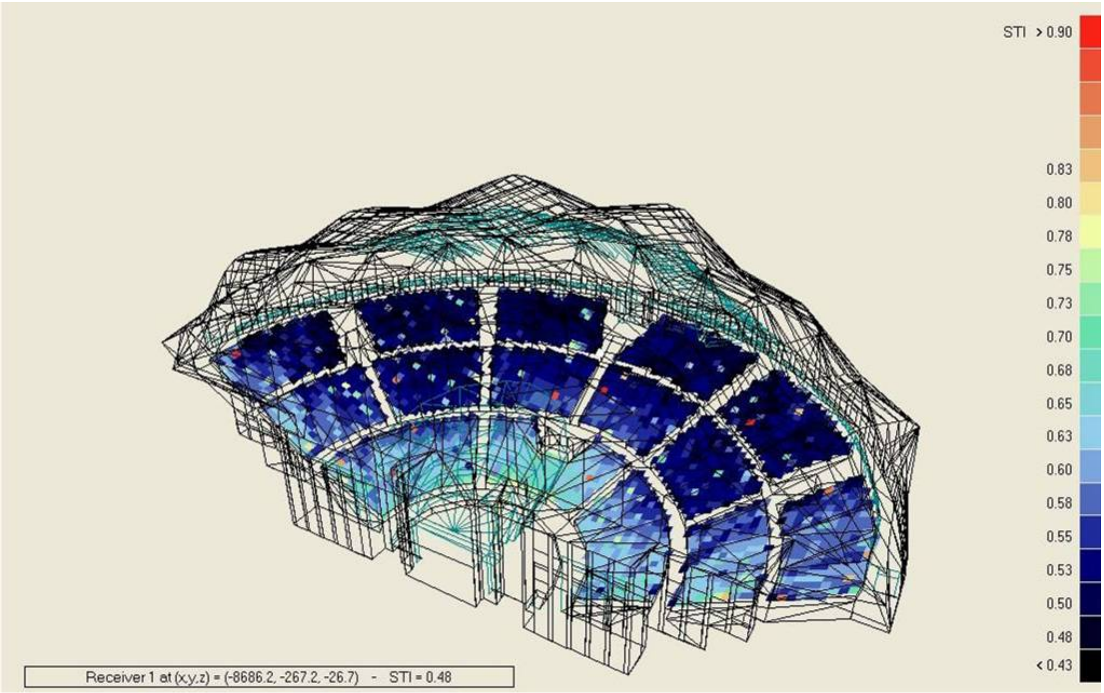


Figure 118. Sound transmission index distribution map for 500 Hz and for the renovated hall.

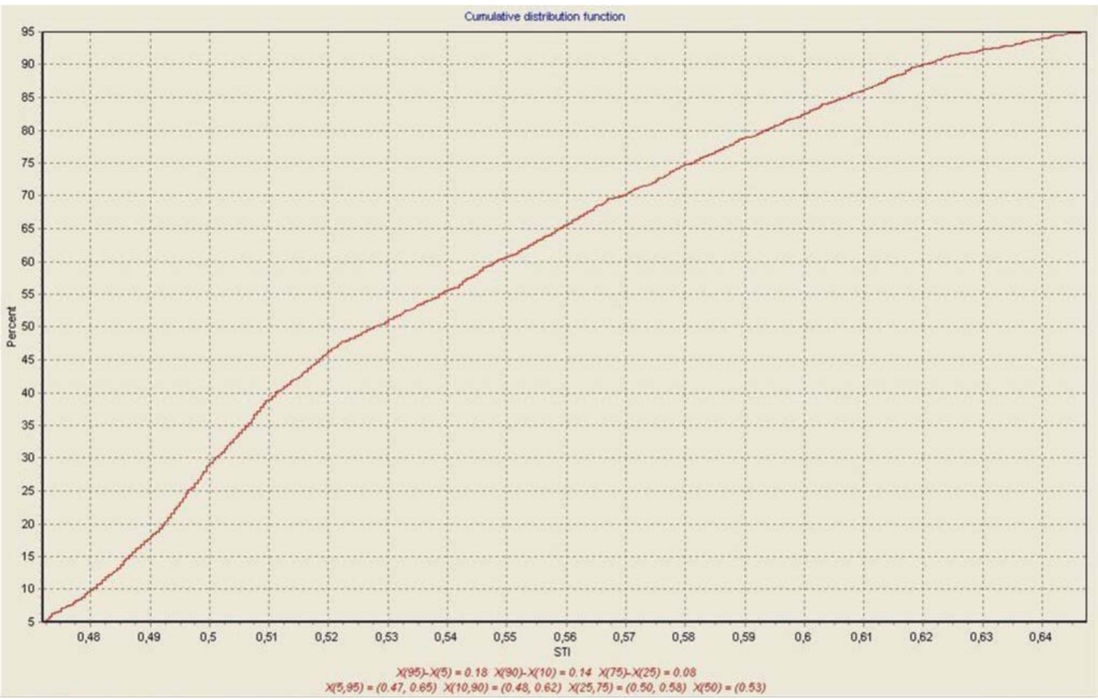


Figure 119. Sound transmission index cumulative distribution graph for the renovated hall.

The global estimation calculations are followed by the grid responses, first of which is the reverberation time distribution. The decrease in the reverberation time is mentioned before. Looking at the overall distribution throughout the hall in the Figure 94., Figure 95., Figure 96. and Figure 97., it is observed that the field becomes much even. The problematic spots with excessive reverberation times implying echoes and sound focuses are halved and are seen in the much fewer locations throughout the hall.

Coming to the EDT maps, the Figure 98., Figure 99., Figure 100. and Figure 101. show that the range is decreased to 1.75 to 3.3 s from 2.3 to 4 s for 500 Hz which is corresponding to a 17% decrease with some seats in the optimum range, whereas almost none of the seats of the present hall is in the acceptable range for the parameter. The distribution for the EDT is much dependent on the geometry and the distance from the reflective surfaces, so it is expected that the parameter will show a higher variety when compared to the reverberation time.

The next parameter is the clarity. Analyzing the Figure 102., Figure 103., Figure 104. and Figure 105., it is observed that the values are changed from -6 to 2.2 dB to -4 to 2.8 dB for 500 Hz. The ratio of the seats that are falling into the optimum range, especially for the music is increased significantly.

The definition, as given in Figure 106., Figure 107., Figure 108. and Figure 109., is ranging from 0.2 to 0.6 in the renovated hall, while in the present hall it is from 0.14 to 0.55 for 500 Hz. None of the seats are falling below the lower limit in the renovated hall, and it becomes especially better for the music performances. The better values for both the clarity and the definition is due to the extended canopy, which is providing increased level of early reflections.

Another criteria called lateral fraction, as given in Figure 110., Figure 111., Figure 112. and Figure 113., is raised in the upper end of the range from 1.7 to 0.22 for 500 Hz. It is obviously seen from the maps that the areas of the better values at the side rows are extended through the central seats, which is most likely due to the enlarged canopy in this case as well.

For assessing the strength parameter from the SPL maps, which should be greater than 0 dB for especially concert use, the overall gain for the source is given as 31 dB. Analyzing the Figure 114., Figure 115., Figure 116. and Figure 117., it is found that the front tiers and the mid tiers except the mid sides are falling into the acceptable range.

The final parameter is the sound transmission index, which is comparatively better than the other parameters in the present situation as seen from the Figure 118. and Figure 119., but as there are many problematic spots when observed from the reverberation time distributions the tolerable values of STI become masked. Again in the renovated hall the values are range from fair to good class with some increase at the upper limit from 0.63 to 0.64, but this time the reverberation time distribution is better than the present hall and so the STI is less deteriorated.

The reflector coverage is displayed for the renovated hall in order to compare the efficiency of the extended canopy and how it effects the different locations of the hall acoustically.

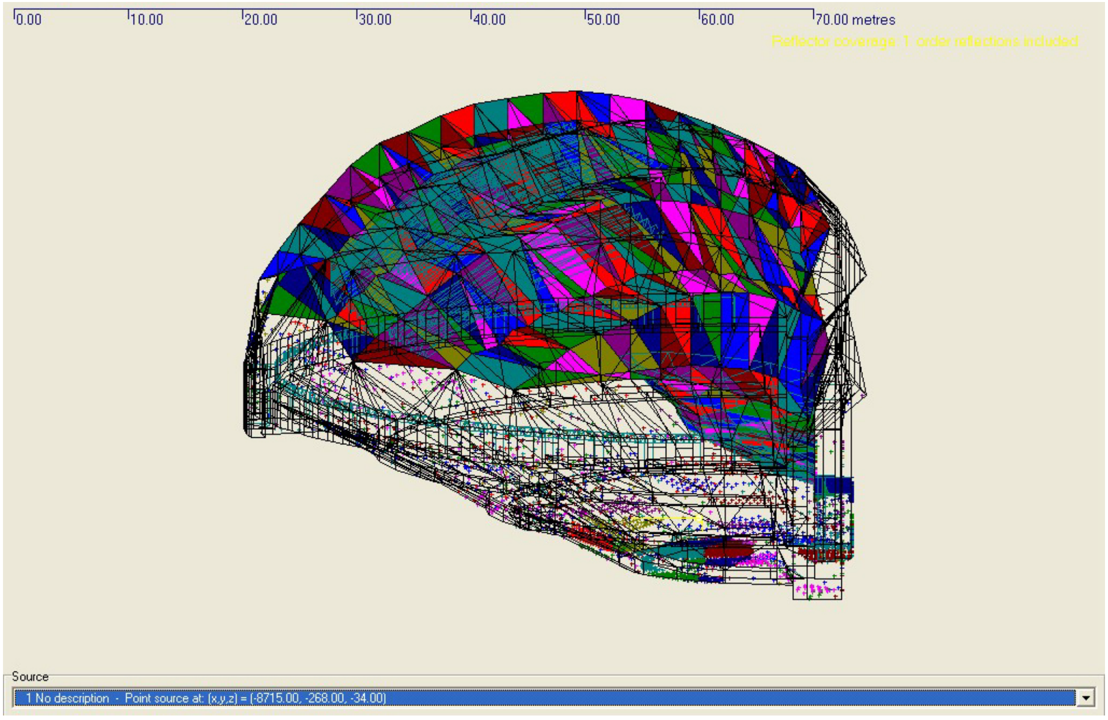


Figure 120. Reflector coverage view 1 for the renovated hall.

In order to compare with the present hall, the reflector coverage figures are observed in the Figure 120. It is apparently found that, the sides of the mid and back tiers have denser reflected sound when compared to the present condition, which is deficient of sound at these seating locations.

7. CONCLUSION

Being the principal objective of the thesis, the analysis of the hall is mostly emphasized in the context of the study. The major method for this analysis is the computer simulation technique, which is checked through other means of acoustical measurements. The different steps of the analysis, results and evaluations are given briefly in the following.

The first step of the study is the assessment of the accuracy of simulation program, which is configurating the basic methodology for the analysis of the problem in this study. As mentioned in Chapter 4, the real-size measurements were concluded in four different parameters, which are calculated for 2 source positions, for 11 receiver points and when the hall is unoccupied. The same parameters are analyzed from the simulation for the corresponding locations when the hall is unoccupied as well. The results show that except the high frequencies above 1000 Hz and low frequencies below 500 Hz, all the values are consistent for all the parameters for the similar locations. As the frequencies that are used in the evaluations of the auditoriums are the mid frequencies which are 500 and 1000 Hz, the simulation software is proved to be applicable in evaluations of the acoustics of Bilkent ODEON for different conditions as well.

In the next step, the simulation software is used for the assessment of the fully-occupied hall. The results show that excessive values of reverberation time causes too much a reverberance and liveness throughout the hall, besides the lack of warmth subjectively. Clarity is undermined by excessive reverberance and the sound becomes blurred. On the other hand, the lower values of lateral fraction results in lack of envelopment for the audience subjectively, and also the lack of room response. The music sounds distant or lack of intimacy, and lack fullness of tone.

Another aspect is the sound level distribution, which shows that the reflectors are not satisfactory in reflecting the sound sufficiently through the hall and the direct sound becomes insufficient at some locations as back and mid sides. By the way, the intelligibility suffers significantly in some seating locations which is observed from the sound transmission index results.

Most of the parameters are out of the optimum range, in addition to the uneven distribution throughout the hall. Rating the hall in total considering the simulation map results, it could be said that the best place in acoustical quality is the central front tiers which is followed by the side fronts, whereas the worst is the back sides which is followed by the mid sides.

The overall condition of the hall is not dynamically responding well with a good uniformity. There are places in the audience area where the sound focuses strongly causing echoes at these points, besides the dead spots. Extensive concave and rigid form of the roof membrane, fan-shaped hall geometry, the excessive volume, and the inadequate amount of diffusing surfaces besides the extremeness of the reflective ones are the main reasons for the echo formation, tone coloration, longer reverberation and poor quality of sound distribution throughout the hall.

In the final step, the suggestions are discussed to improve the acoustical quality of the hall, by aiming a much balanced sound field and decreased amount of above mentioned acoustical defects. These suggestions are involving the reorientation of the fabrics hanged on acoustical bridges, changing the fabric with a nonwoven fabric, extending the over-stage canopy and fragmenting the semi-circular beam of the back arcade.

The suggestions are implemented on the model and the simulation is reworked for the fully-occupied condition. The results show that the reverberation time is decreased by 15%. The bass balance, which is the ratio of mid frequency RT to high frequency RT fall into the optimum range. So, warmth is obtained subjectively. Besides the RT, all of the above mentioned parameters are taken into much reasonable ranges. And, the acoustical defects including echoes, which could be observed from the RT distribution maps, are lessened in significant amounts. So, the distribution of the sound becomes much even when compared to the present condition. And finally, it is observed that the reflected sound becomes denser at the sides of the mid and back tiers when compared to the present distribution of the sound.

It is clearly observed from the study that the major surfaces in an auditorium have important implications on the acoustical quality of a place. In order to avoid acoustical defects the precautions has to be taken at the design stage, as their elimination in a completed hall is a difficult and in some cases even an impossible task. In the case of Bilkent ODEON an improvement is obtained, however a wholly perfect solution with logical and economical ways is facing difficulties considering the excessive volume and the semi-open condition of the hall, which is exposed to the atmospheric effects. Consequently, a further study could be the research of new materials that have sound absorption properties and durable against these atmospheric conditions, besides the nonwoven fabric. Moreover, the construction methods and the economic aspects of the suggestions should be studied on, while developing new ones by taking into consideration the complete analysis of the hall.

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APPENDIX A

ARCHITECTURAL DRAWINGS
OF
BİLKENT ODEON

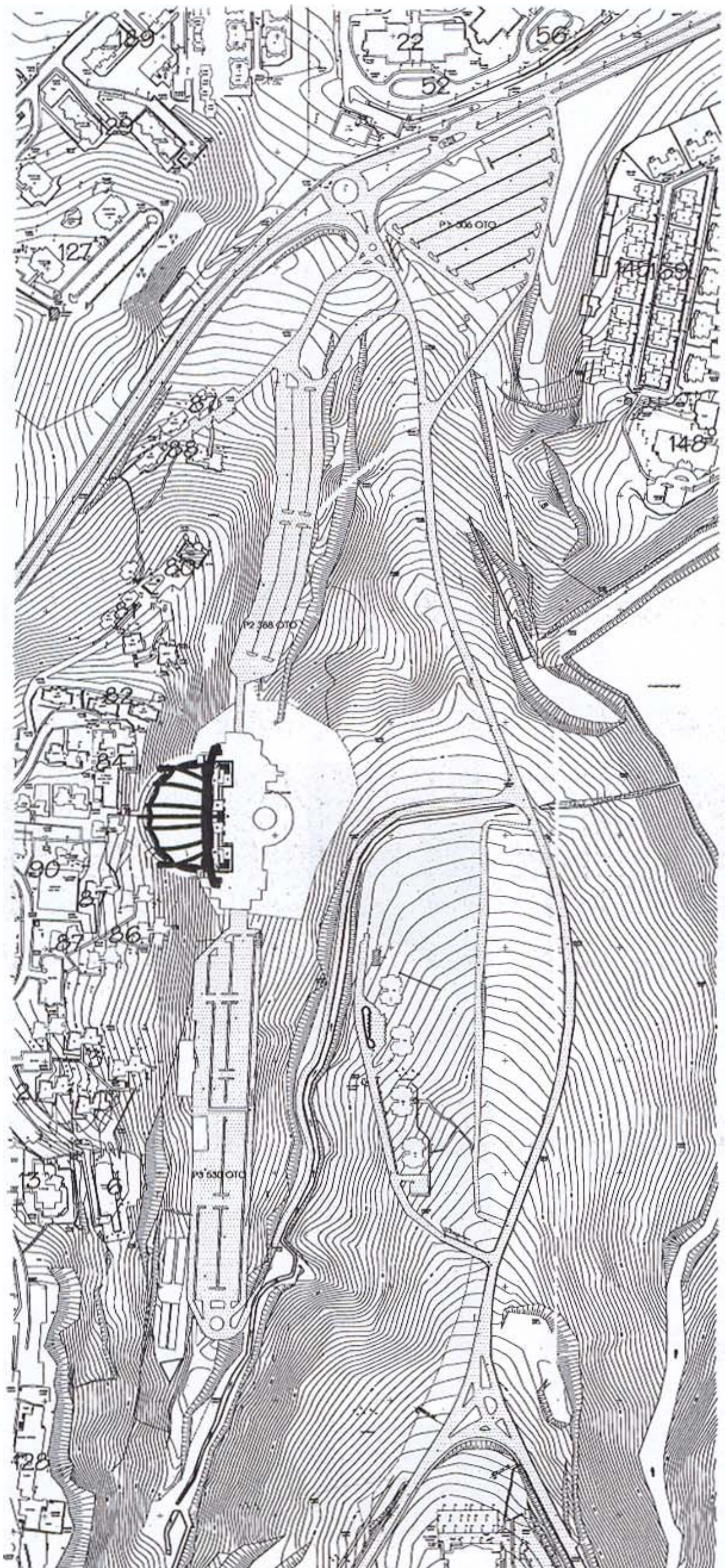

Figure 121. Site plan of Bilkent ODEON.

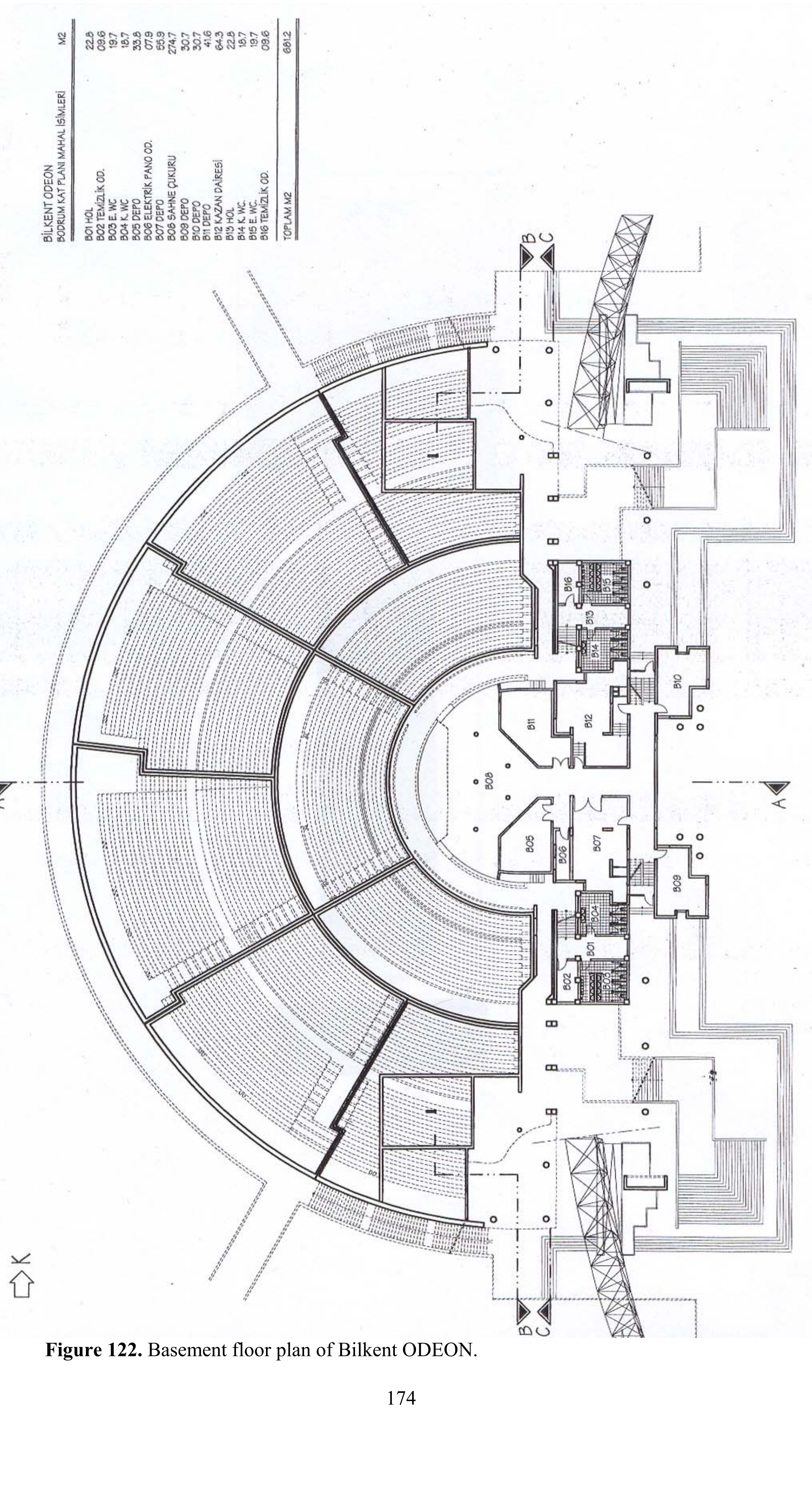

Figure 122. Basement floor plan of Bilkent ODEON.

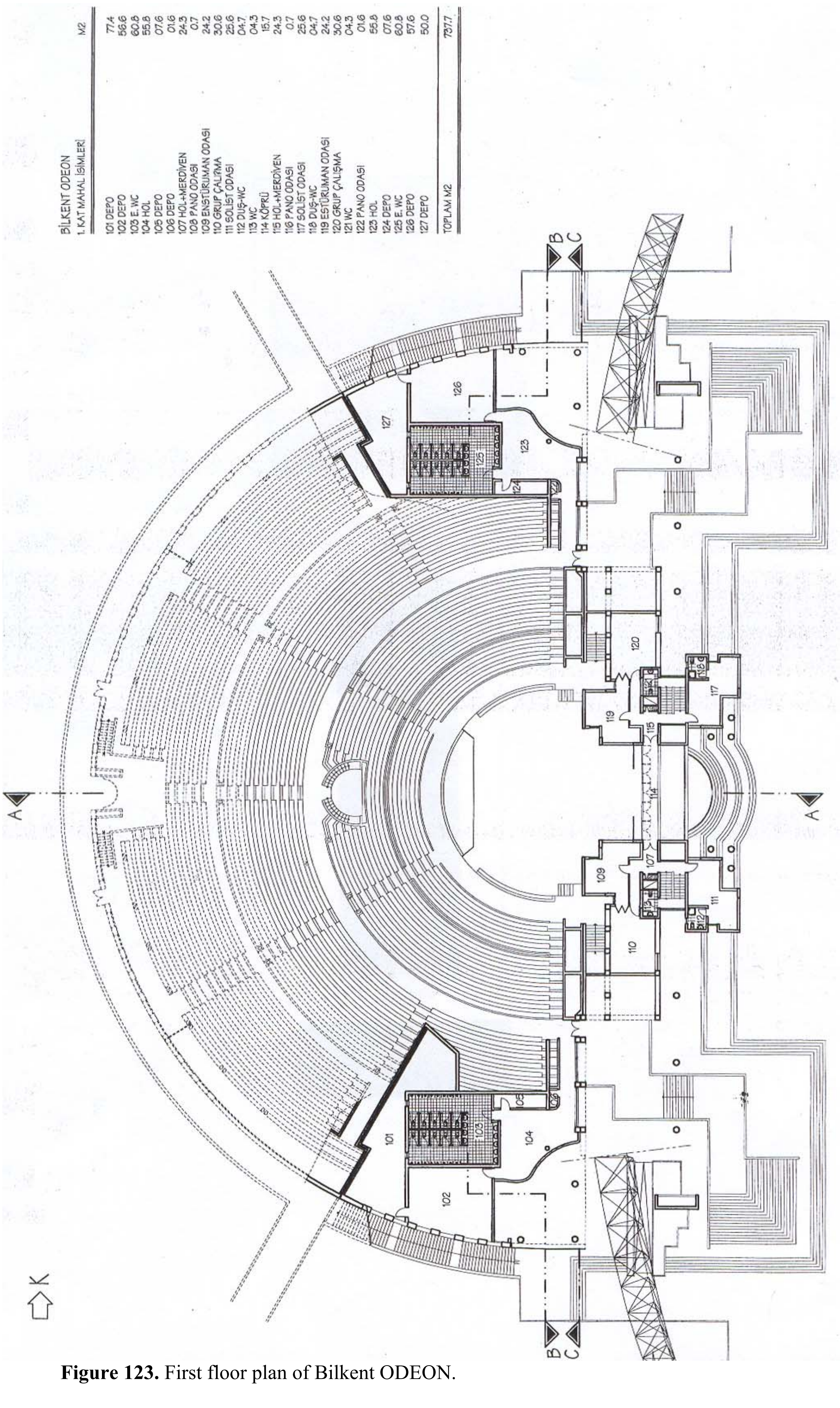

Figure 123. First floor plan of Bilkent ODEON.

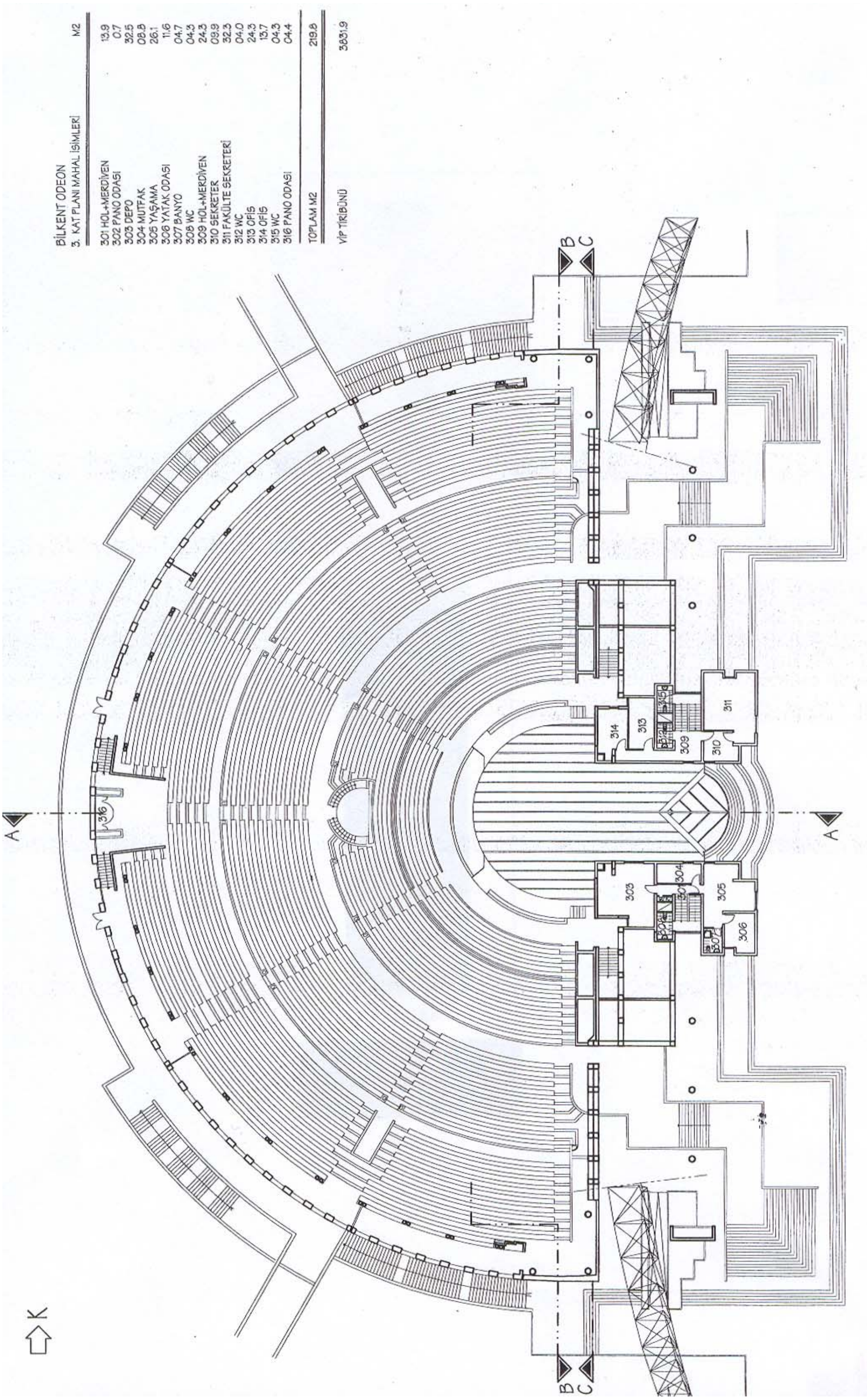

Figure 124. Second floor plan of Bilkent ODEON.

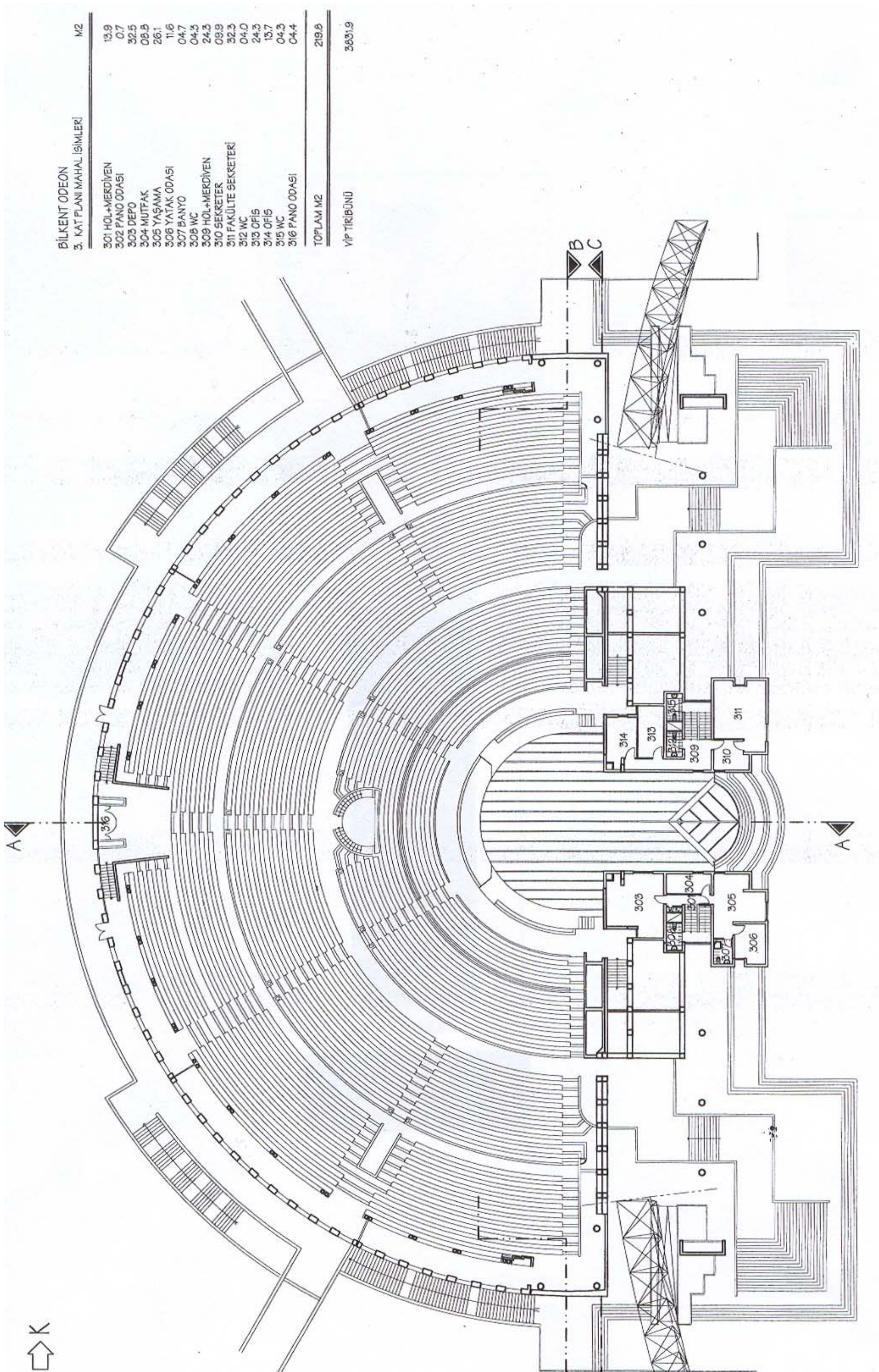

Figure 125. Third floor plan of Bilkent ODEON.

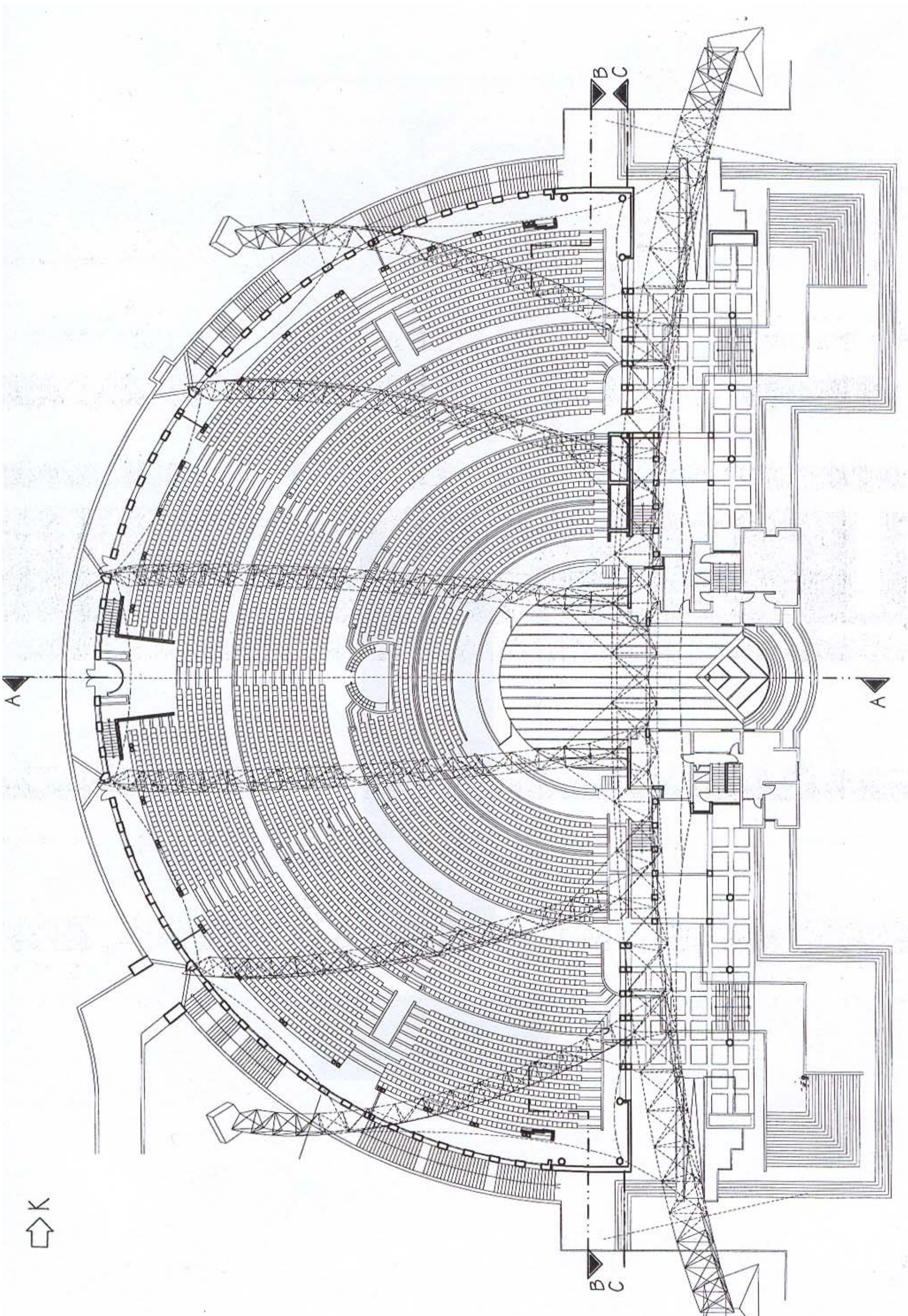

Figure 126. Steel truss construction plan of Bilkent ODEON.

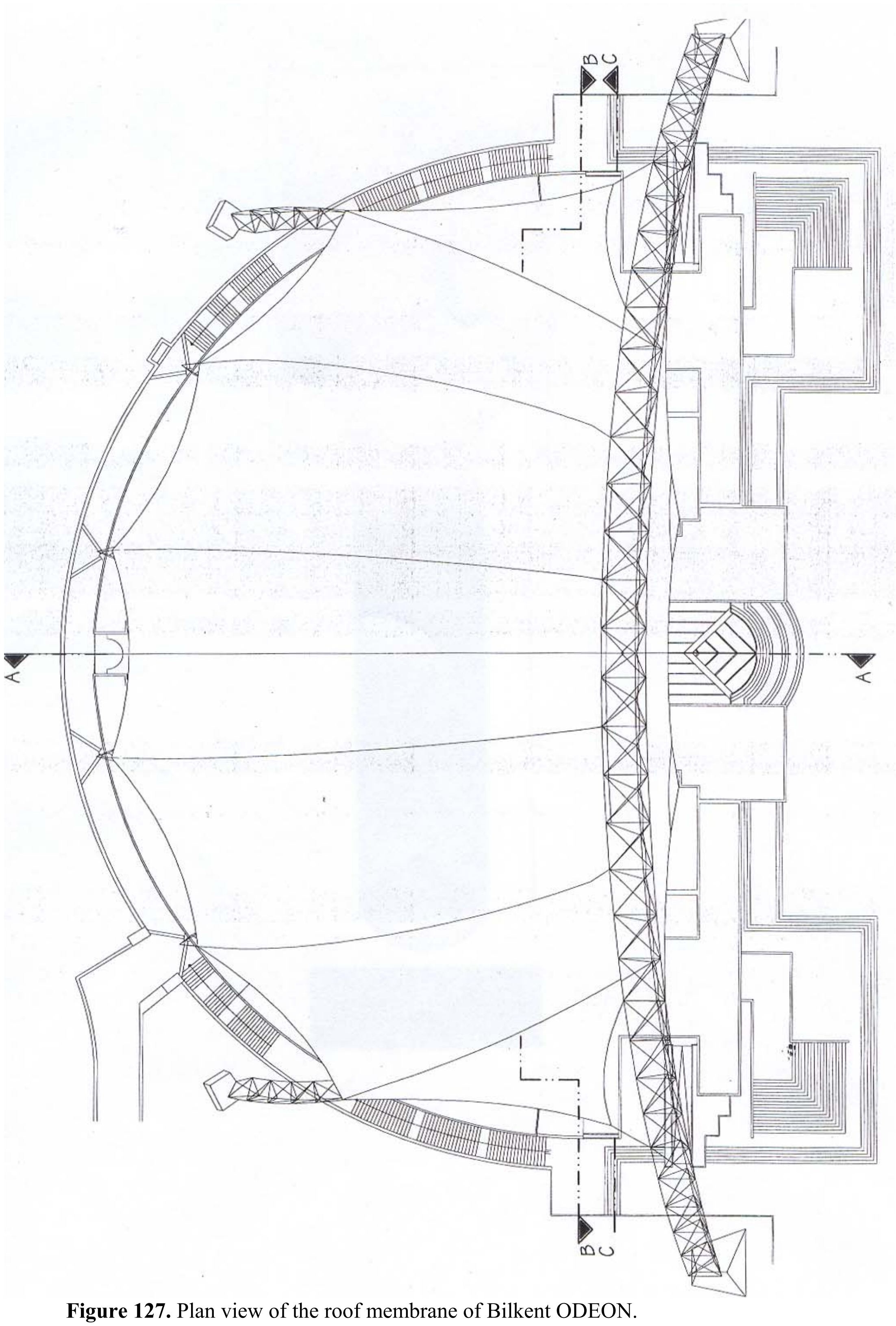

Figure 127. Plan view of the roof membrane of Bilkent ODEON.

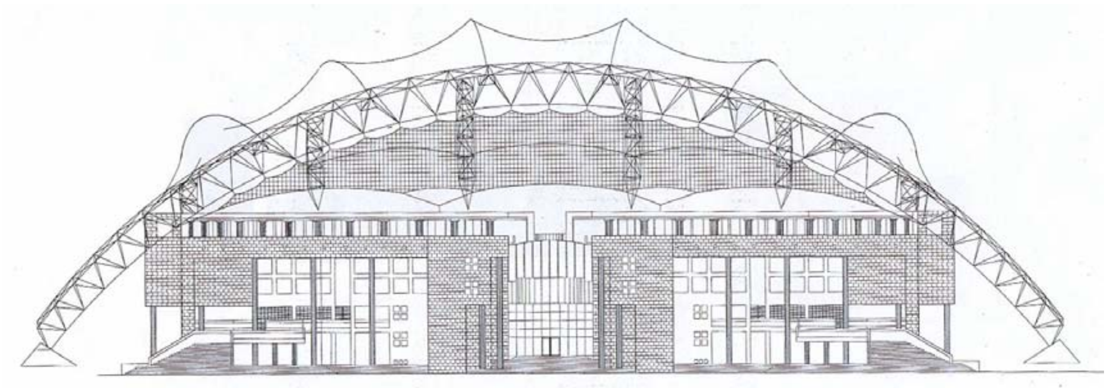

Figure 128. East elevation of Bilkent ODEON.

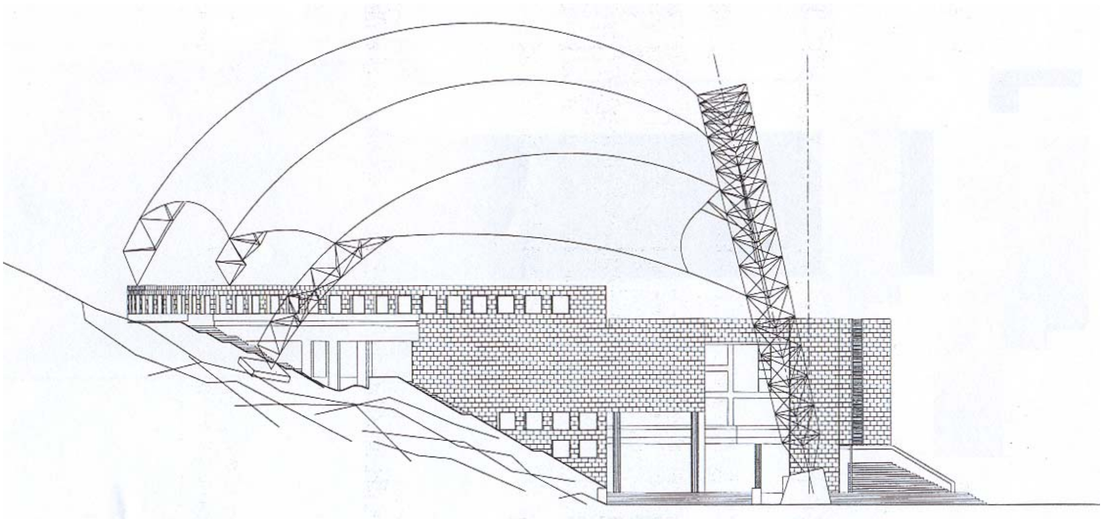

Figure 129. South elevation of Bilkent ODEON.

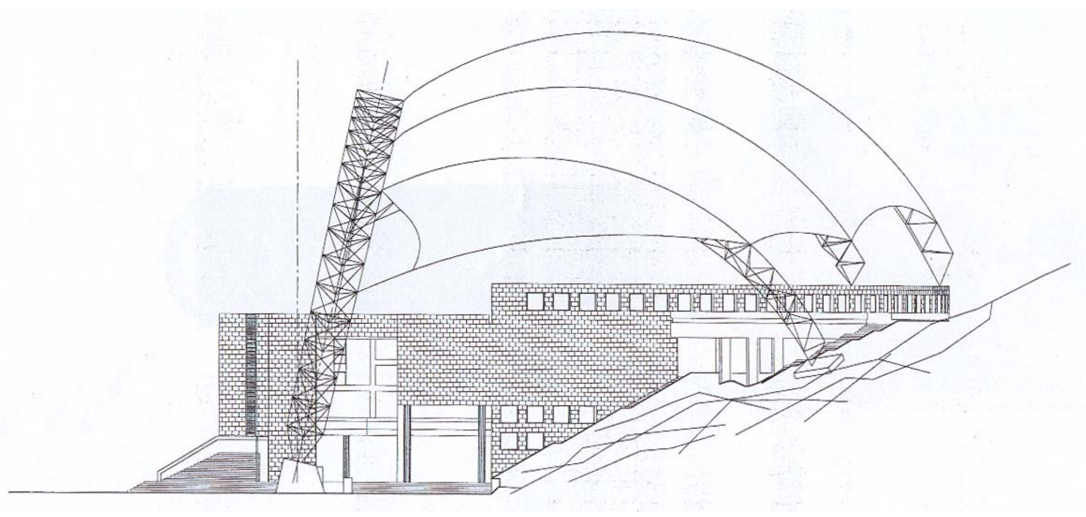

Figure 130. North elevation of Bilkent ODEON.

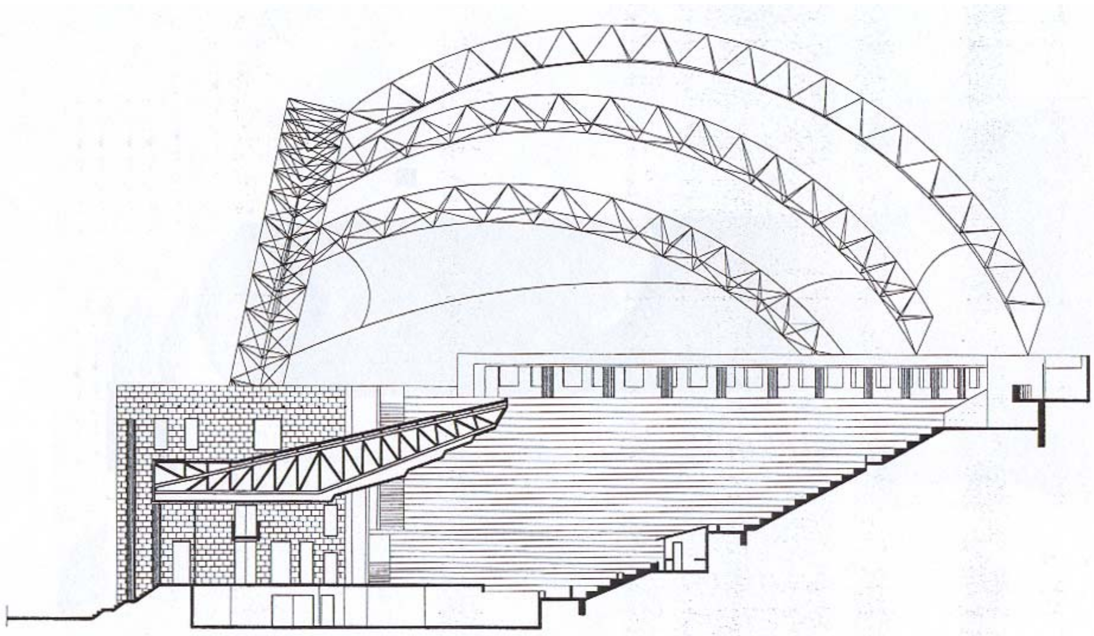

Figure 131. Section A-A of Bilkent ODEON.

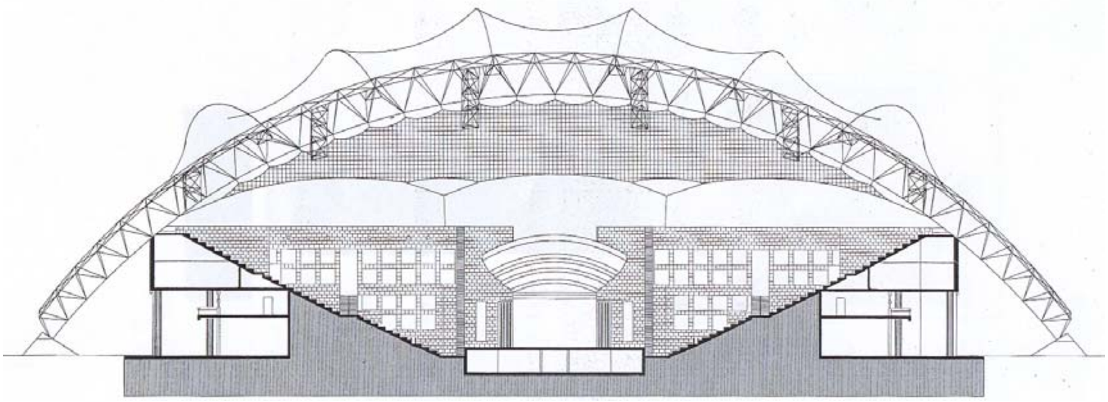

Figure 132. Section B-B of Bilkent ODEON.

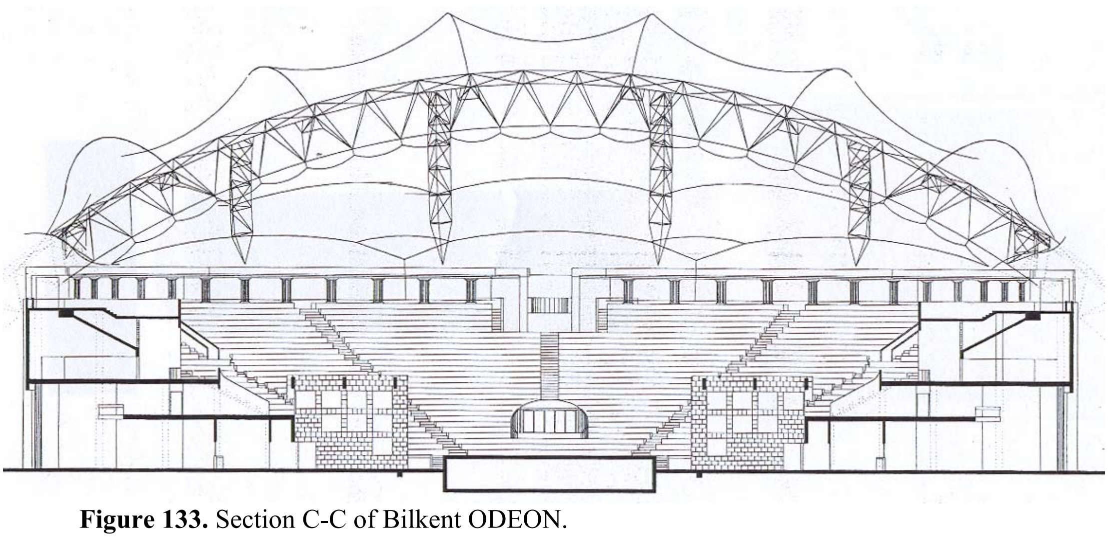

Figure 133. Section C-C of Bilkent ODEON.

APPENDIX B

MLSSA RESULTS

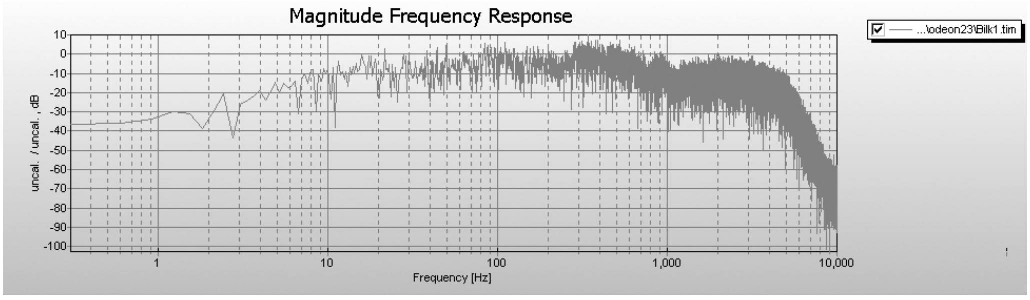

Figure 134. Magnitude frequency response graph for the receiver location A1.

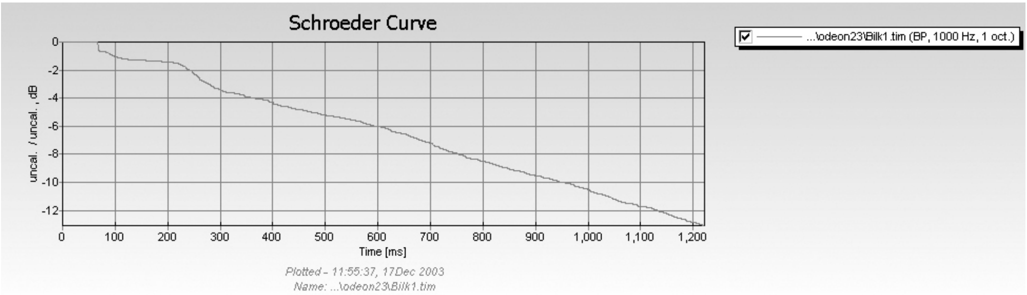

Figure 135. Schroeder curve for the receiver location A1.

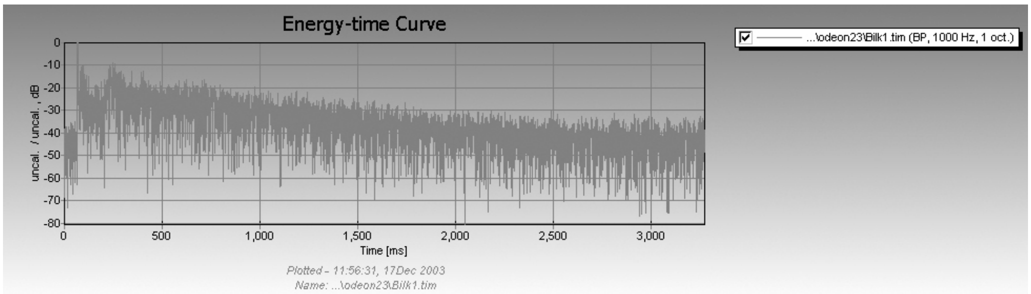

Figure 136. Energy-time curve for the receiver location A1.

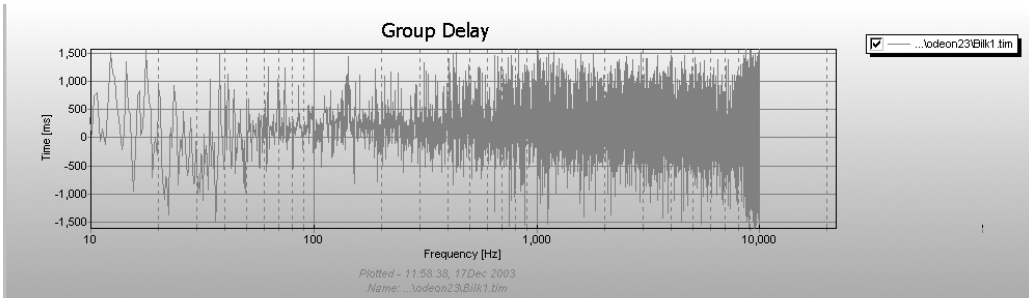

Figure 137. Group delay graph for the receiver location A1.

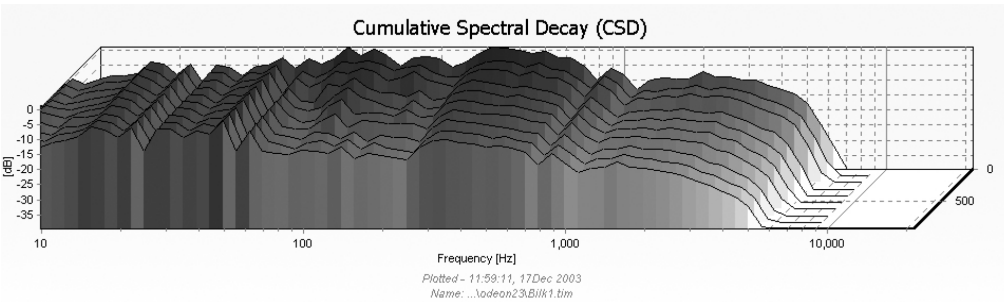

Figure 138. Cumulative spectral decay graph for the receiver location A1.

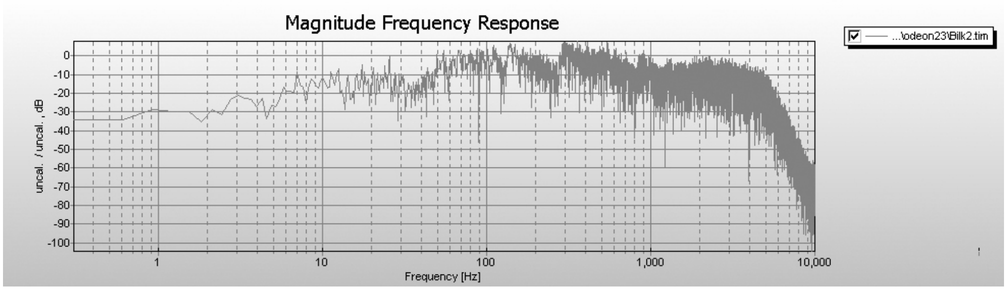

Figure 139. Magnitude frequency response graph for the receiver location A2.

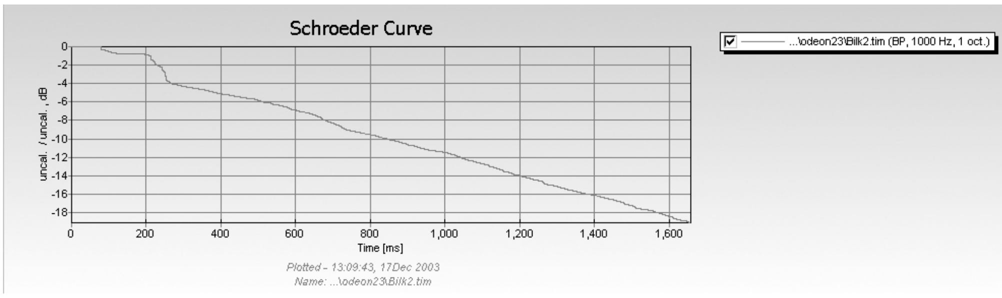

Figure 140. Schroeder curve for the receiver location A2.

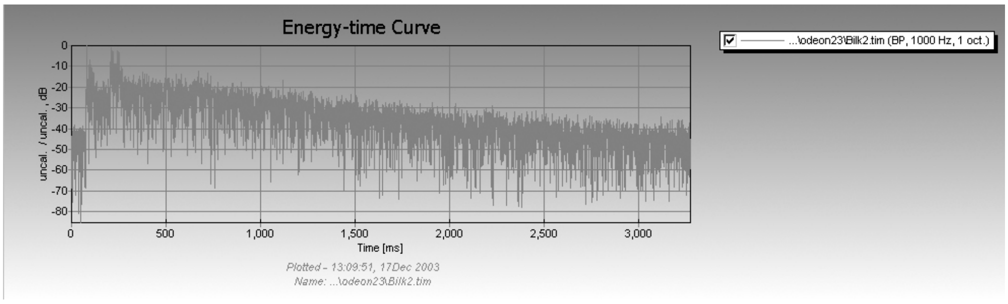

Figure 141. Energy-time curve for the receiver location A2.

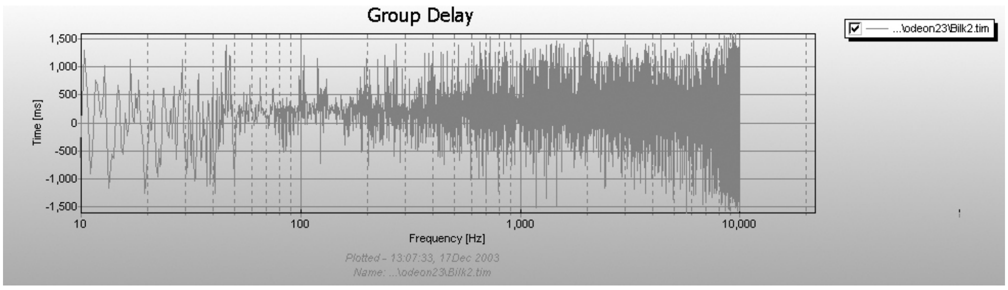

Figure 142. Group delay graph for the receiver location A2.

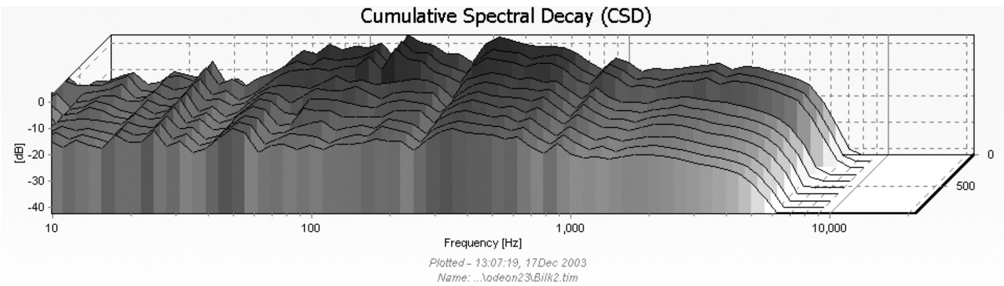

Figure 143. Cumulative spectral decay graph for the receiver location A2.

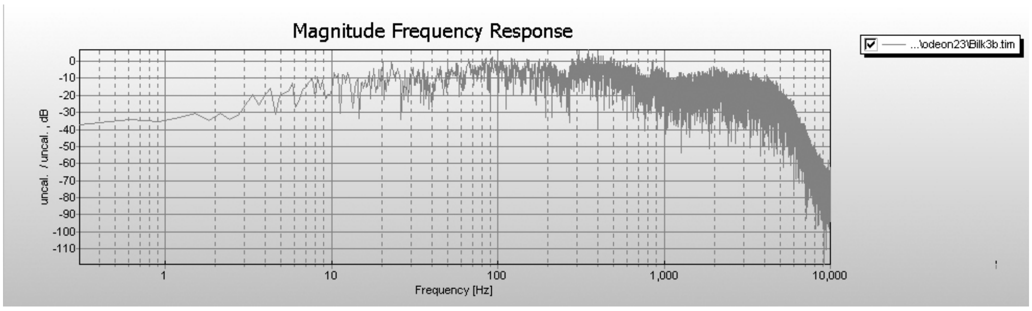

Figure 144. Magnitude frequency response graph for the receiver location A3.

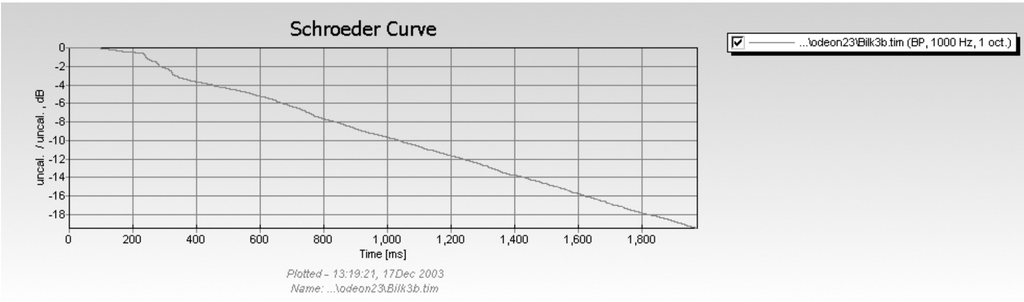

Figure 145. Schroeder curve for the receiver location A3.

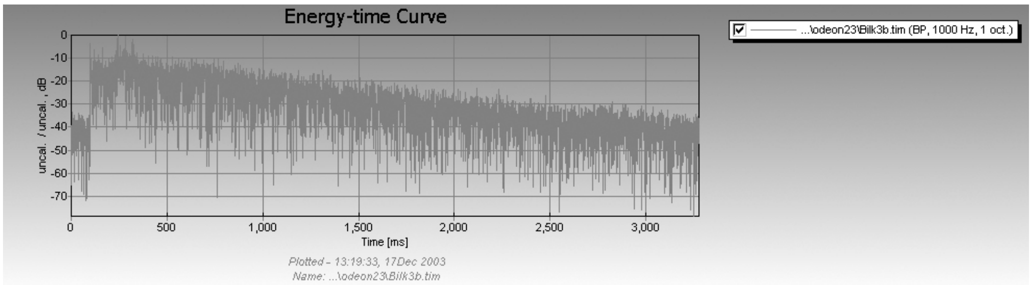

Figure 146. Energy-time curve for the receiver location A3.

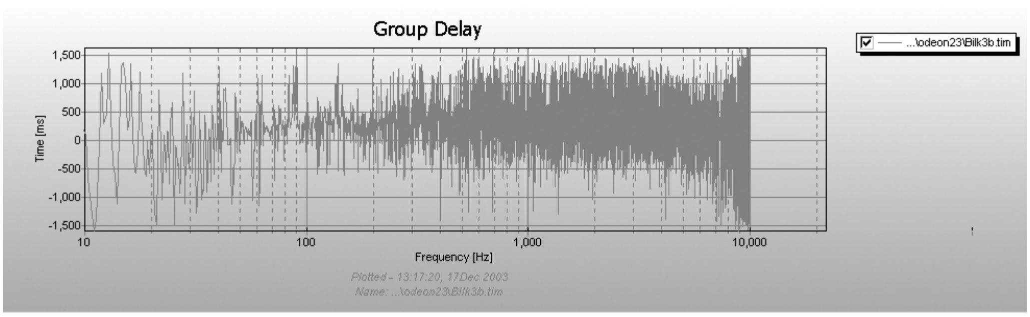

Figure 147. Group delay graph for the receiver location A3.

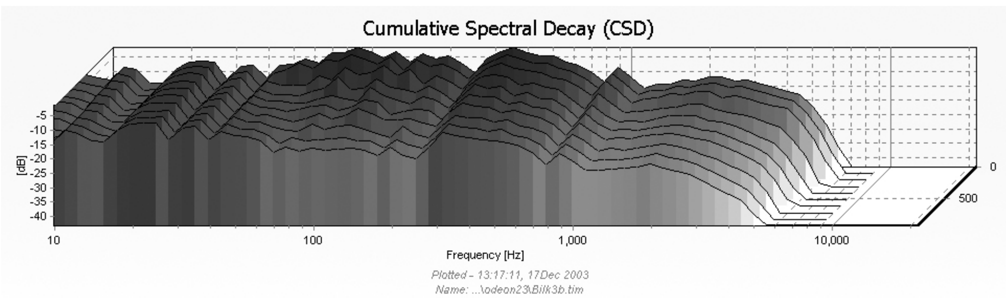

Figure 148. Cumulative spectral decay graph for the receiver location A3.

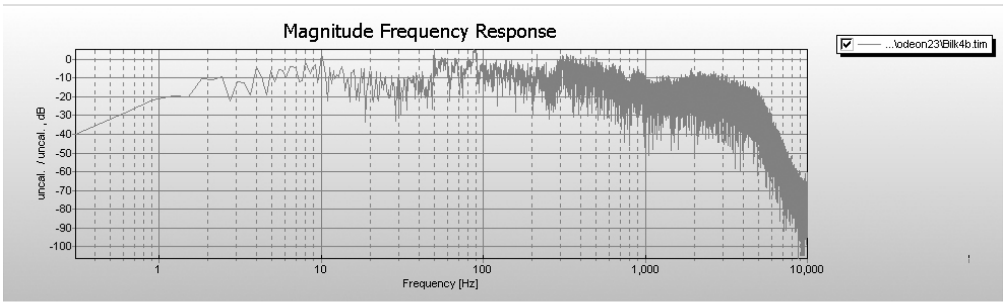

Figure 149. Magnitude frequency response graph for the receiver location A4.

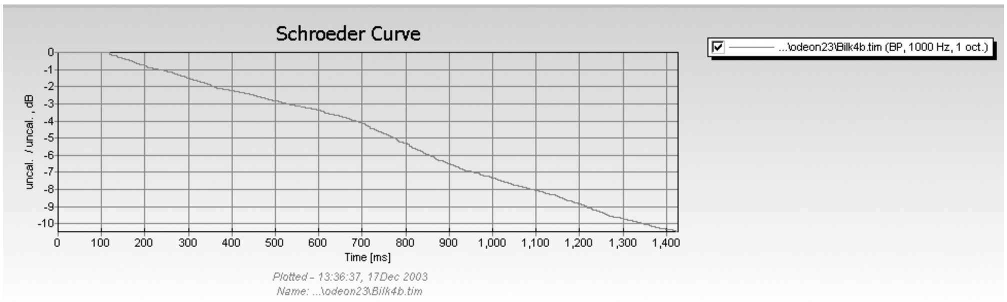

Figure 150. Schroeder curve for the receiver location A4.

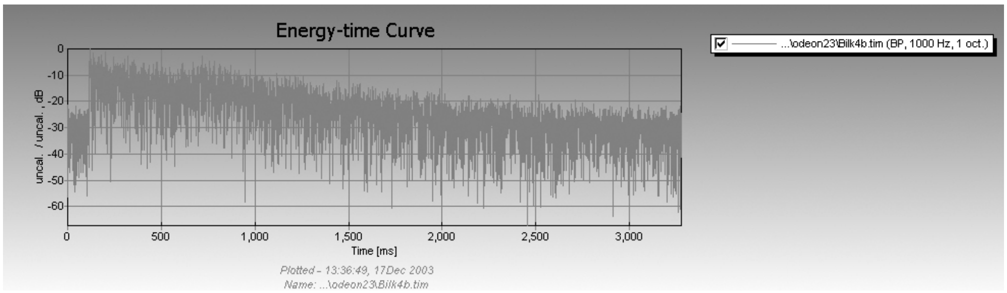

Figure 151. Energy-time curve for the receiver location A4.

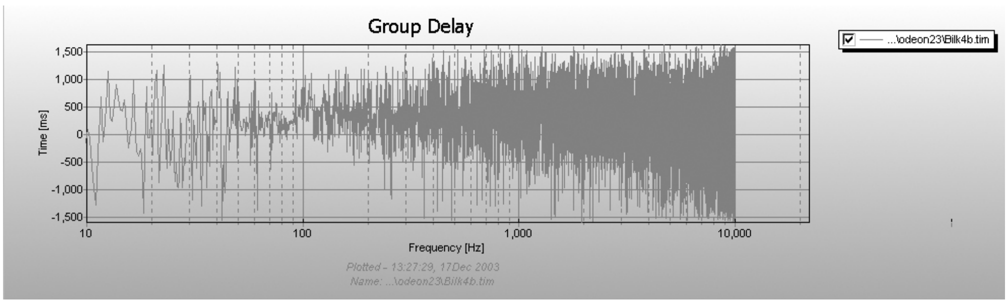

Figure 152. Group delay graph for the receiver location A4.

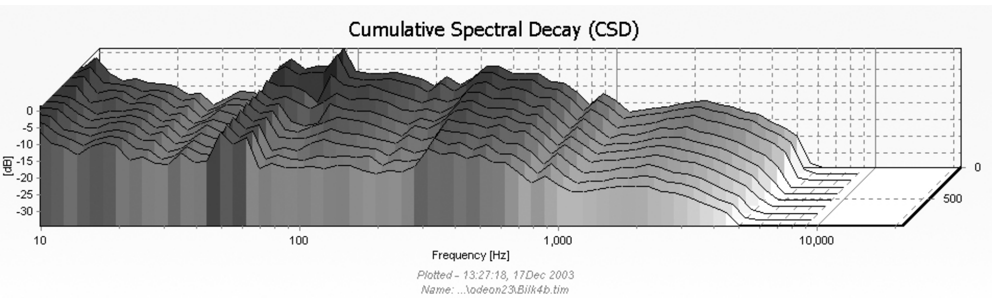

Figure 153. Cumulative spectral decay graph for the receiver location A4.

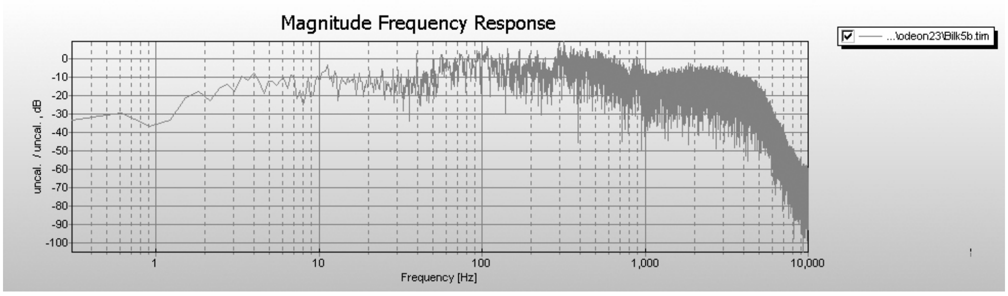

Figure 154. Magnitude frequency response graph for the receiver location A5.

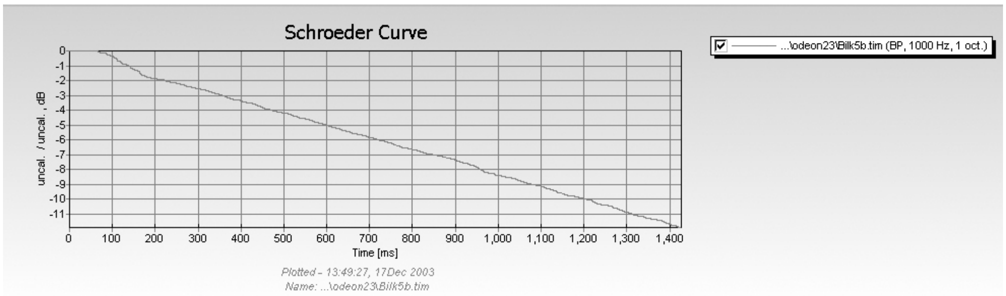

Figure 155. Schroeder curve for the receiver location A5.

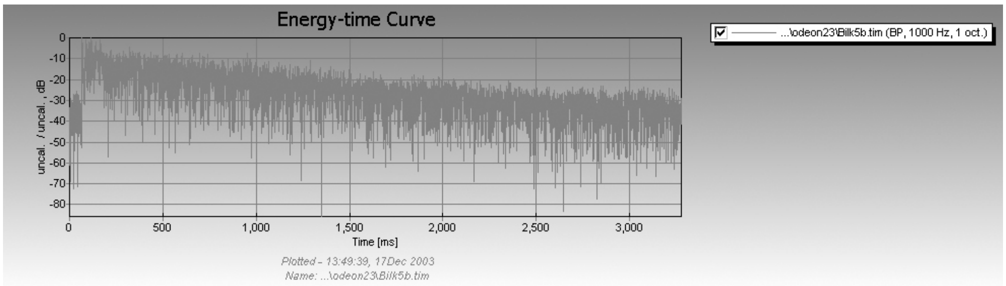

Figure 156. Energy-time curve for the receiver location A5.

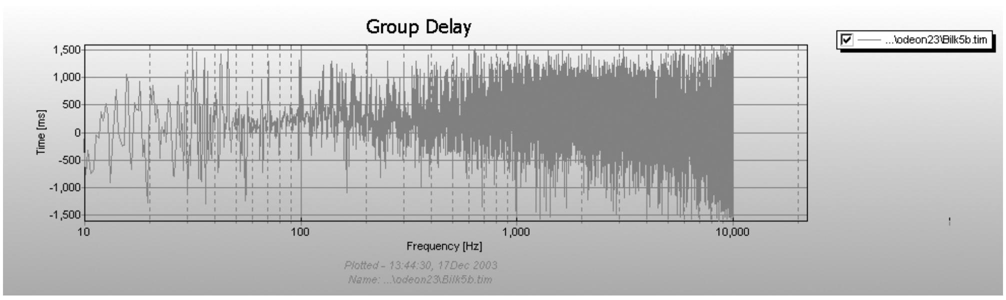

Figure 157. Group delay graph for the receiver location A5.

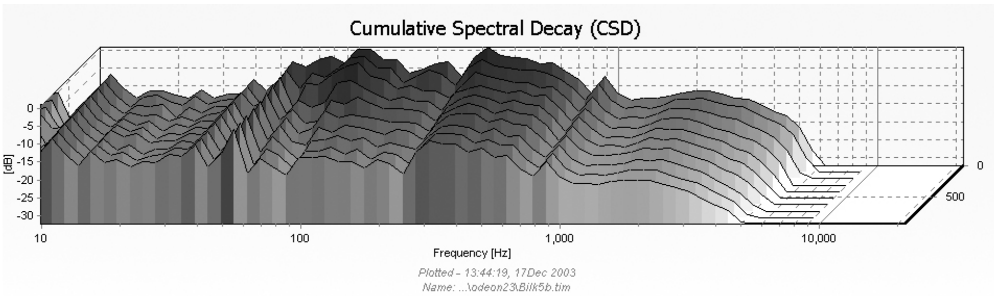

Figure 158. Cumulative spectral decay graph for the receiver location A5.

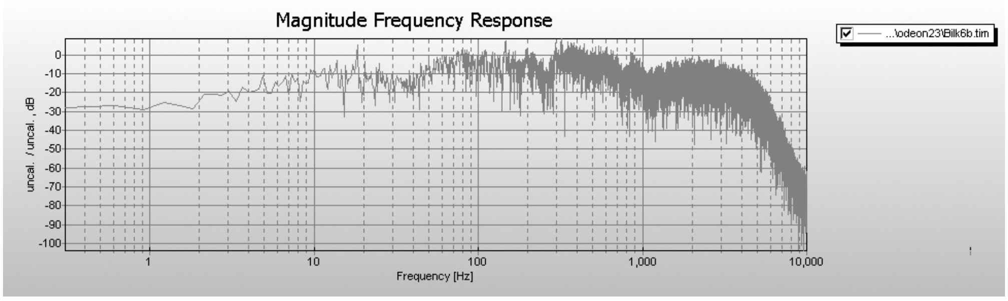

Figure 159. Magnitude frequency response graph for the receiver location A6.

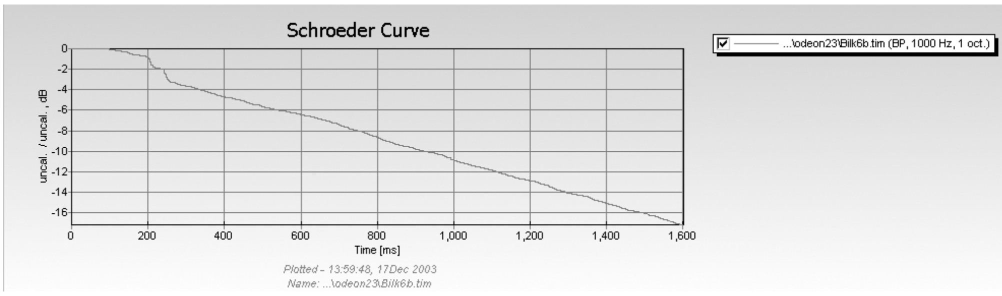

Figure 160. Schroeder curve for the receiver location A6.

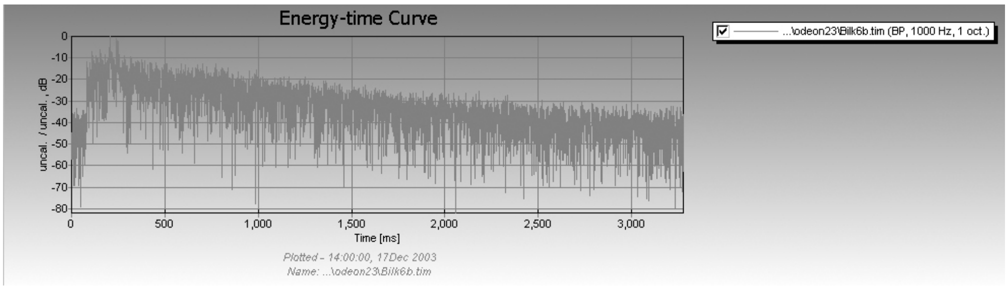

Figure 161. Energy-time curve for the receiver location A6.

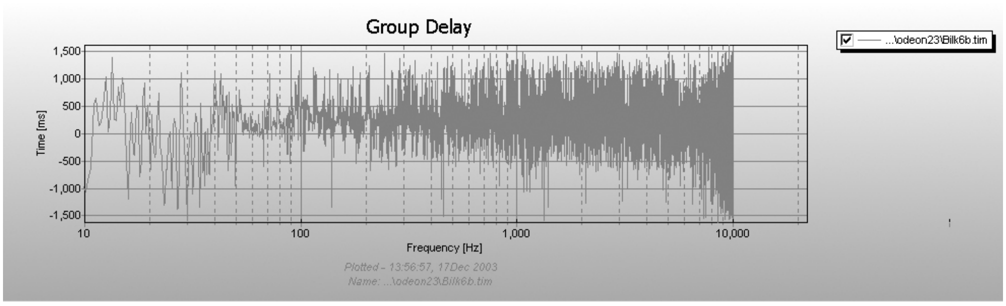

Figure 162. Group delay graph for the receiver location A6.

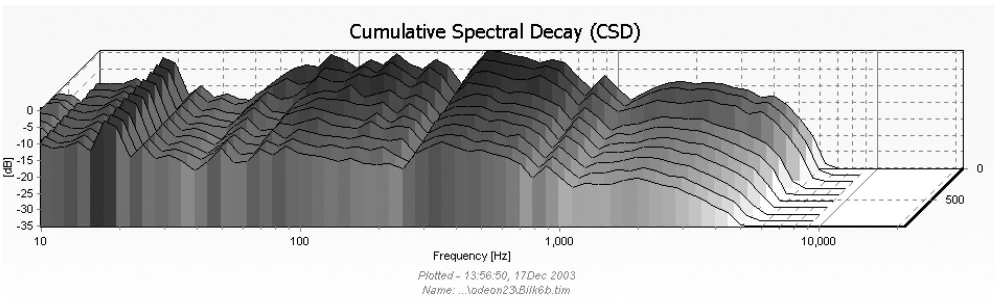

Figure 163. Cumulative spectral decay graph for the receiver location A6.

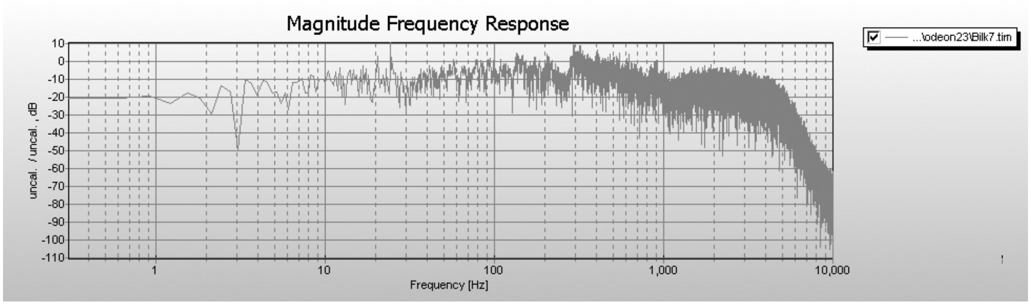

Figure 164. Magnitude frequency response graph for the receiver location A7.

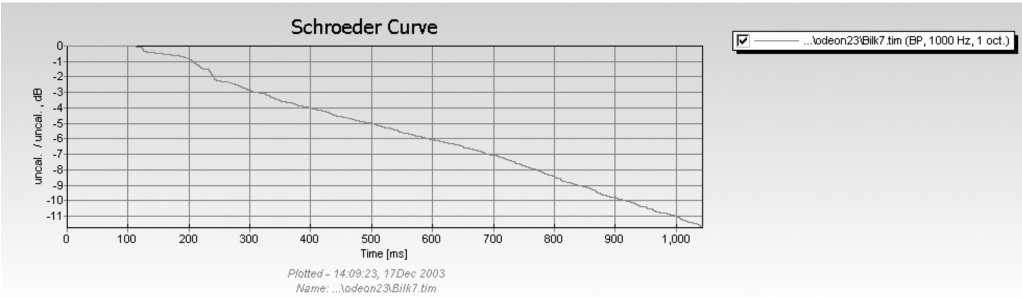

Figure 165. Schroeder curve for the receiver location A7.

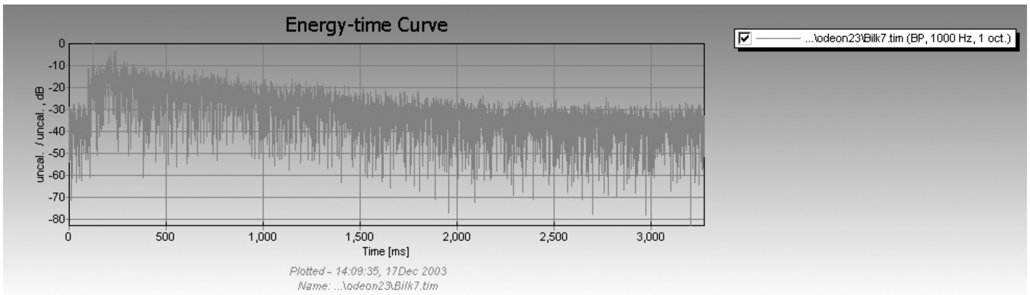

Figure 166. Energy-time curve for the receiver location A7.

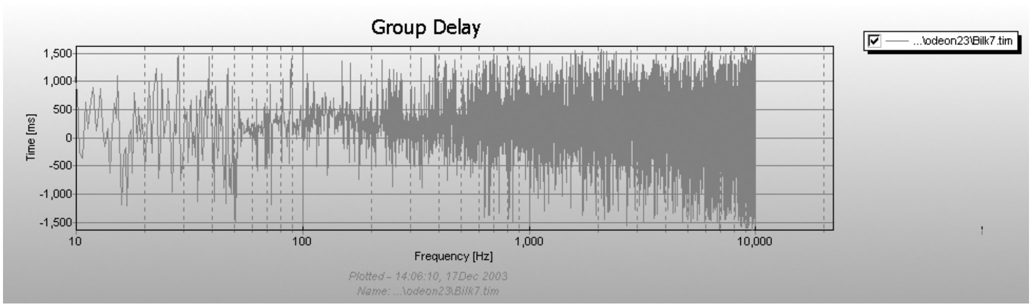

Figure 167. Group delay graph for the receiver location A7.

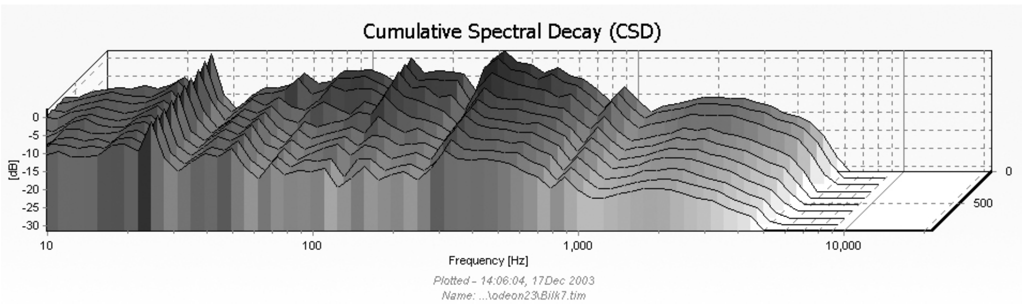

Figure 168. Cumulative spectral decay graph for the receiver location A7.

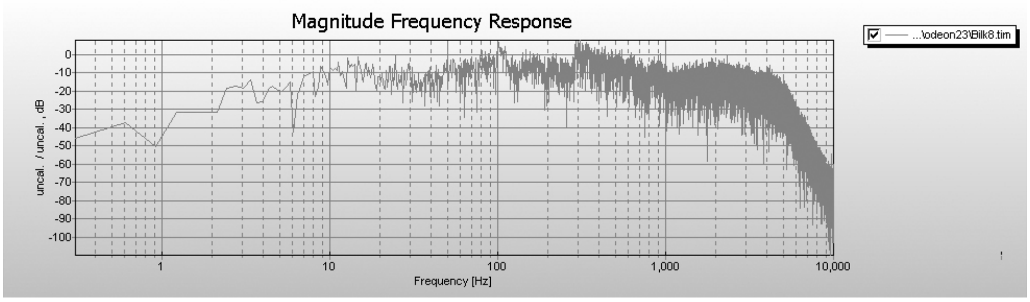

Figure 169. Magnitude frequency response graph for the receiver location A8.

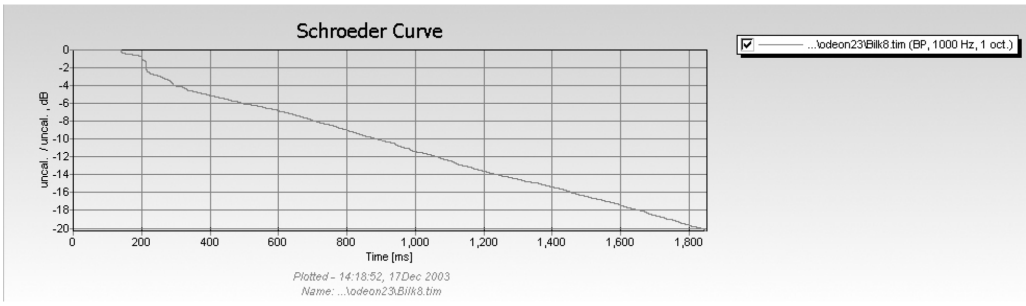

Figure 170. Schroeder curve for the receiver location A8.

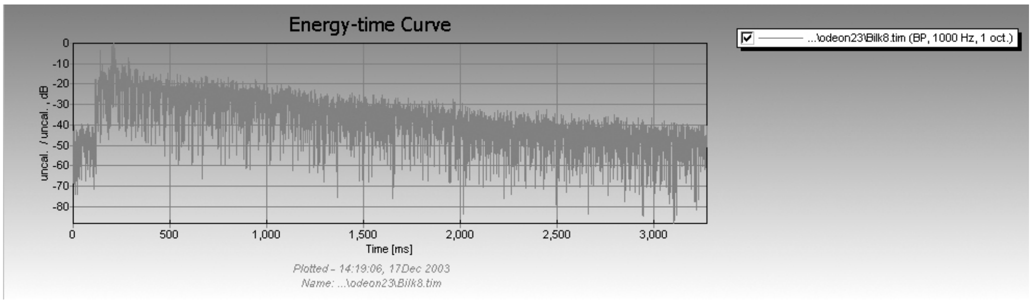

Figure 171. Energy-time curve for the receiver location A8.

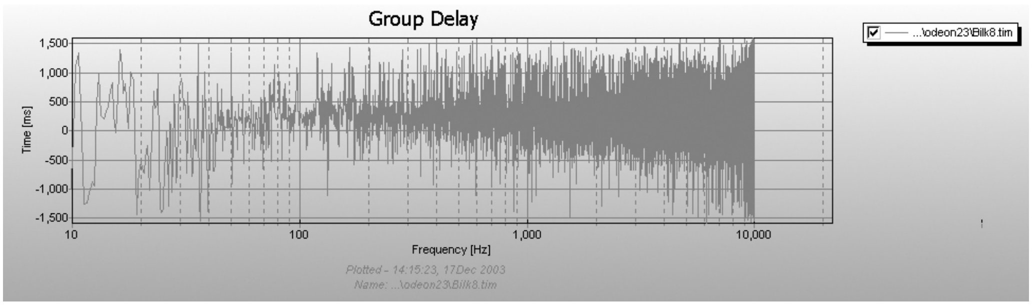

Figure 172. Group delay graph for the receiver location A8.

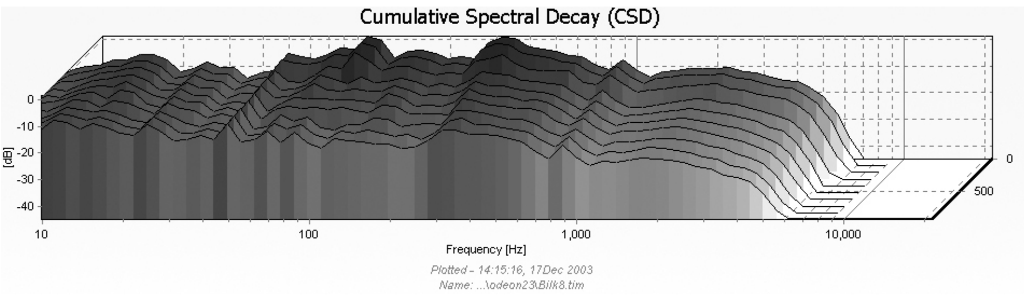

Figure 173. Cumulative spectral decay graph for the receiver location A8.

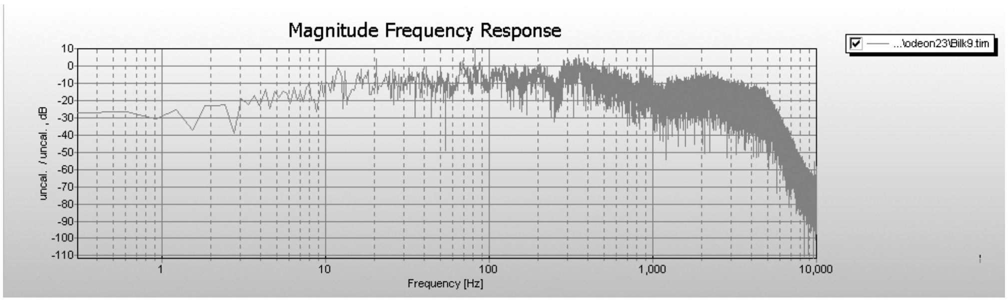

Figure 174. Magnitude frequency response graph for the receiver location A9.

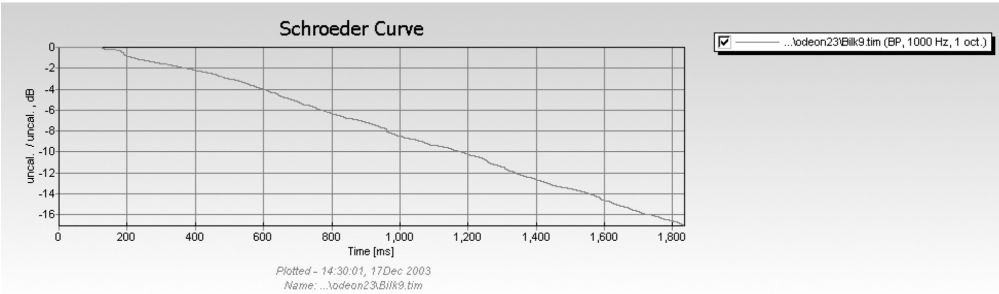

Figure 175. Schroeder curve for the receiver location A9.

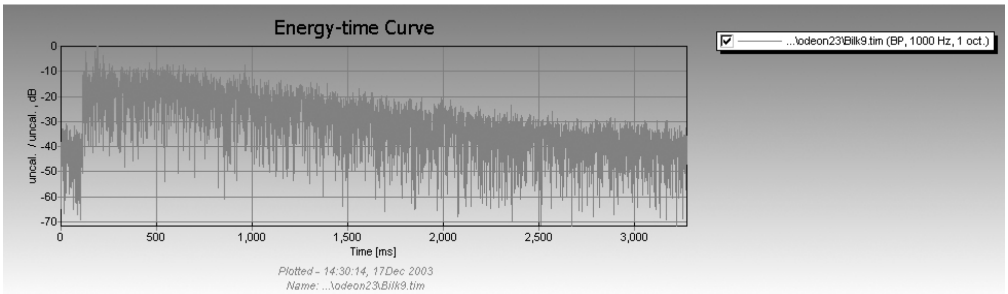

Figure 176. Energy-time curve for the receiver location A9.

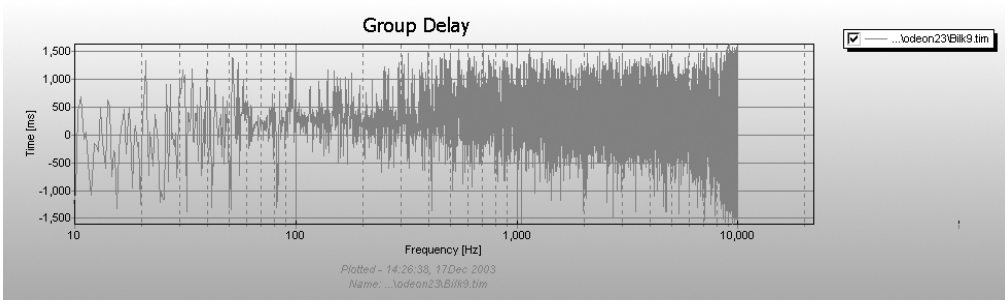

Figure 177. Group delay graph for the receiver location A9.

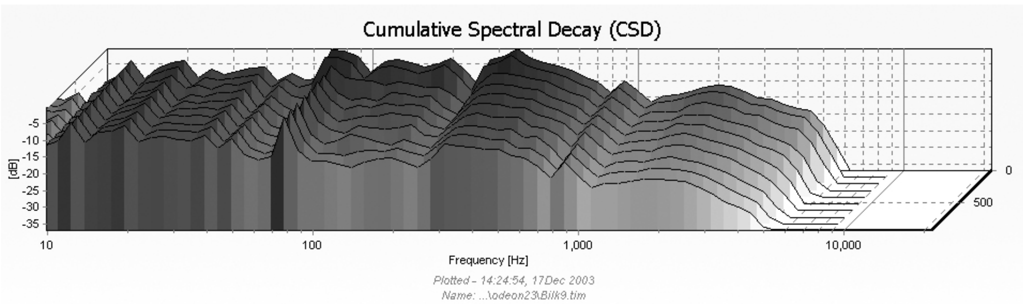

Figure 178. Cumulative spectral decay graph for the receiver location A9.

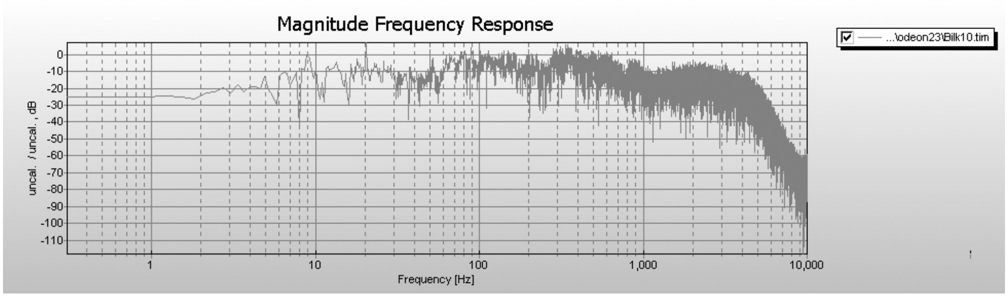

Figure 179. Magnitude frequency response graph for the receiver location A10.

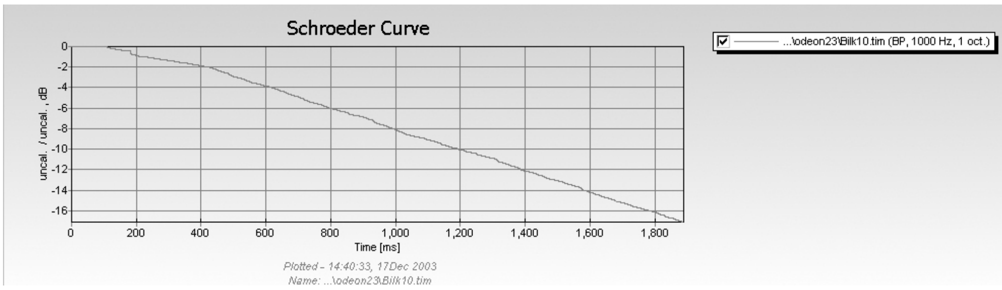

Figure 180. Schroeder curve for the receiver location A10.

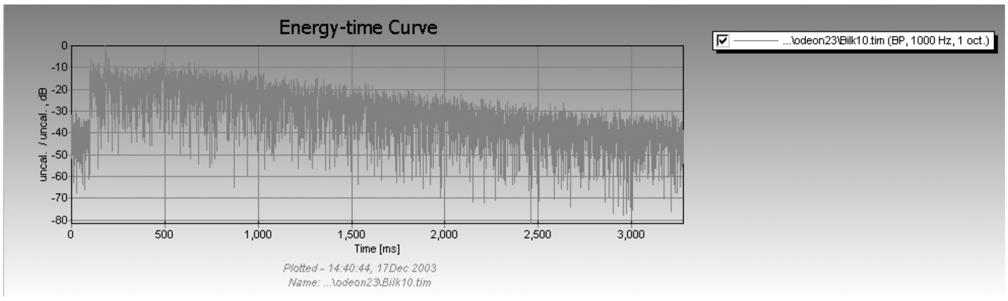

Figure 181. Energy-time curve for the receiver location A10.

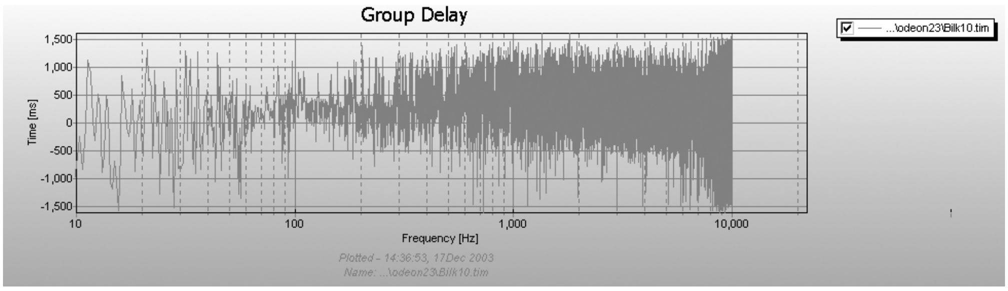

Figure 182. Group delay graph for the receiver location A10.

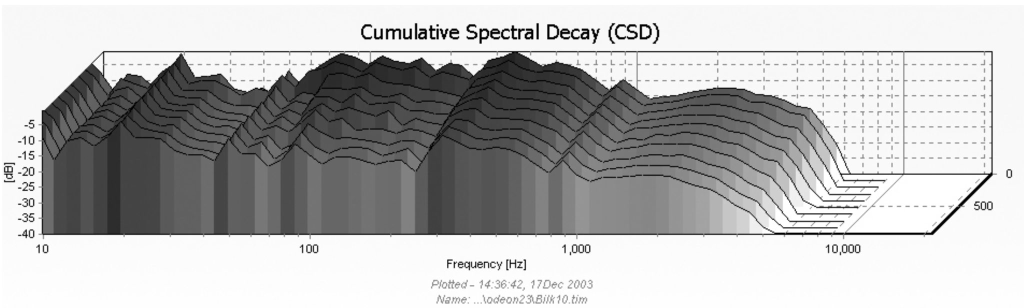

Figure 183. Cumulative spectral decay graph for the receiver location A10.

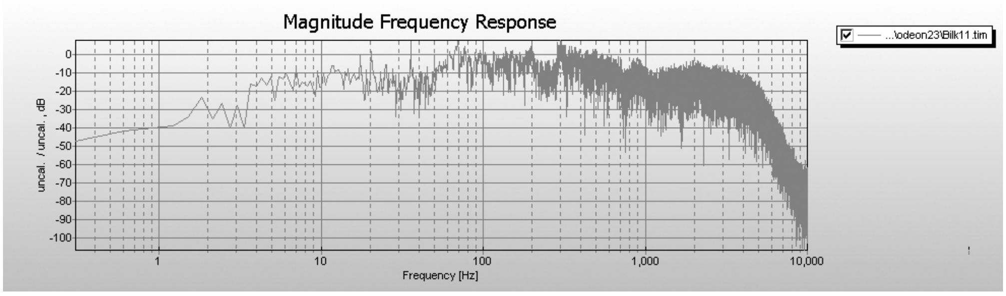

Figure 184. Magnitude frequency response graph for the receiver location A11.

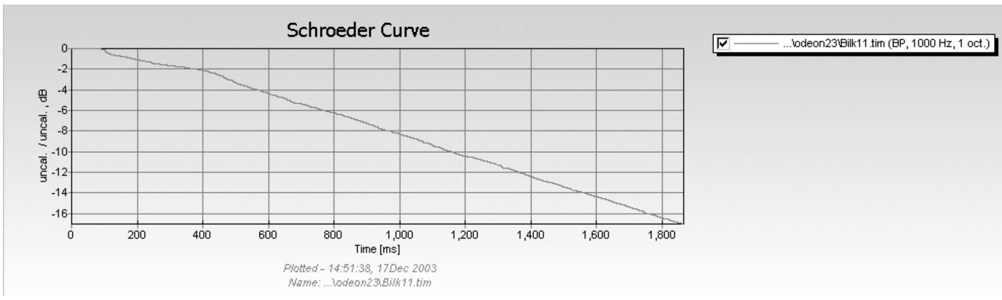

Figure 185. Schroeder curve for the receiver location A11.

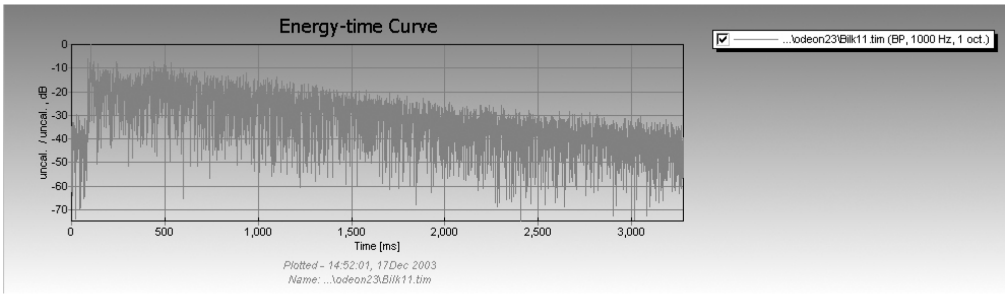

Figure 186. Energy-time curve for the receiver location A11.

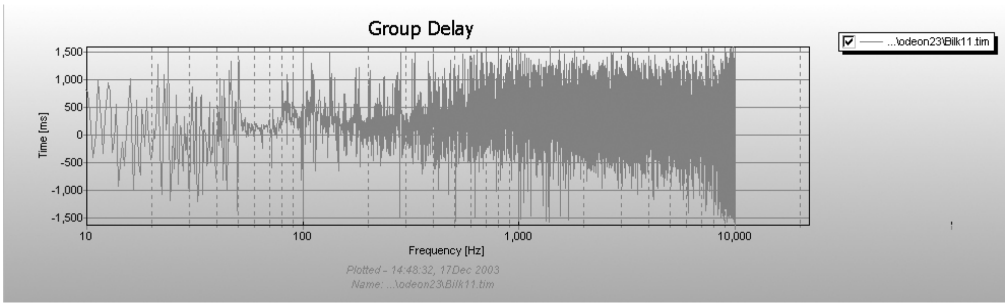

Figure 187. Group delay graph for the receiver location A11.

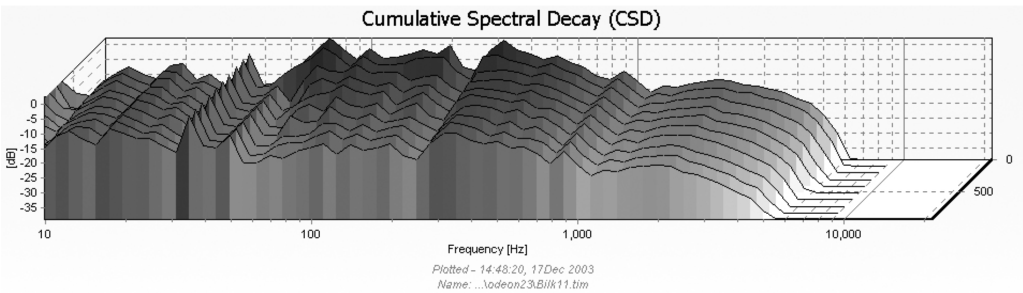

Figure 188. Cumulative spectral decay graph for the receiver location A11.

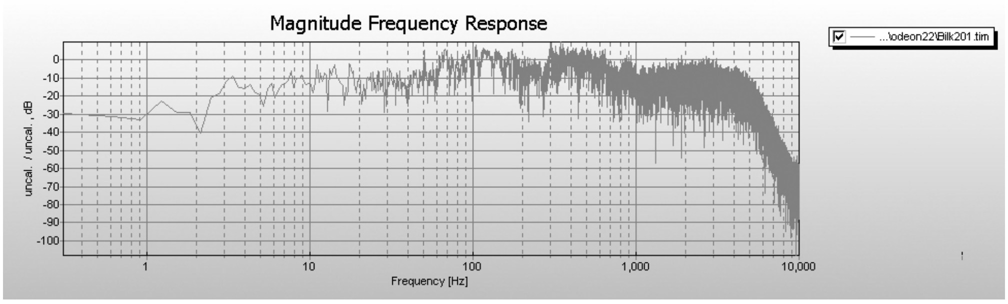

Figure 189. Magnitude frequency response graph for the receiver location B1.

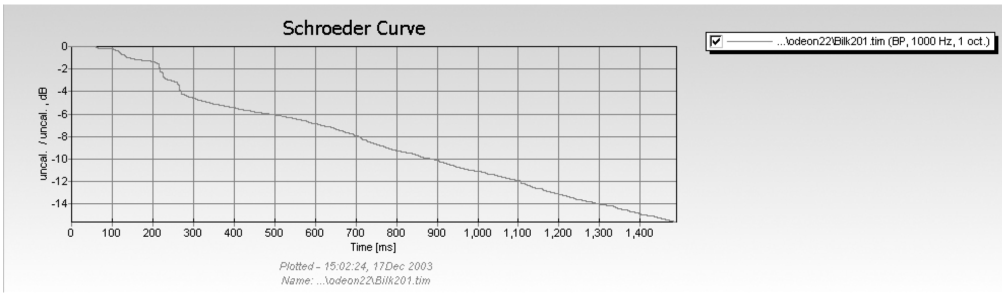

Figure 190. Schroeder curve for the receiver location B1.

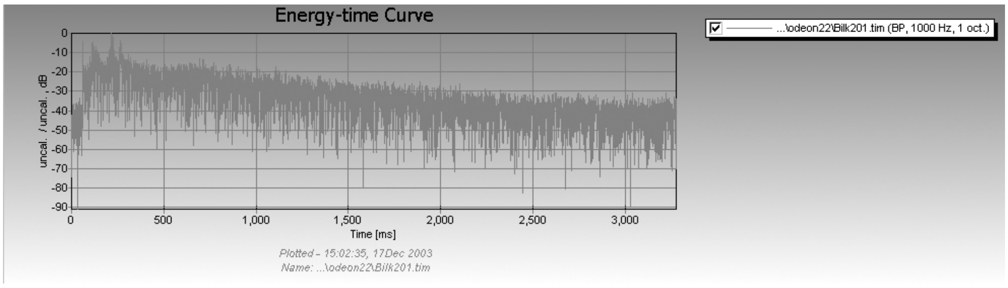

Figure 191. Energy-time curve for the receiver location B1.

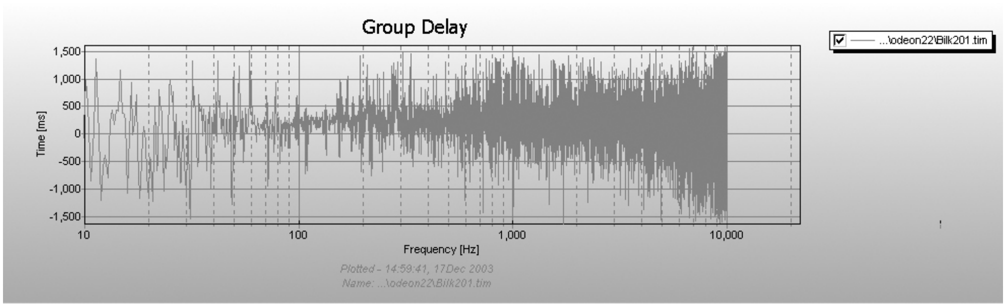

Figure 192. Group delay graph for the receiver location B1.

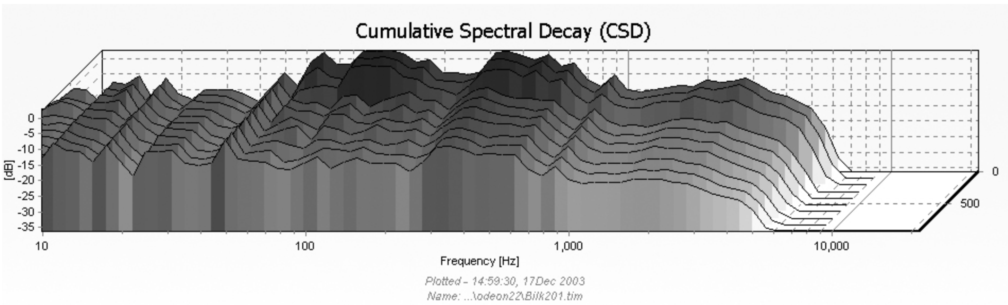

Figure 193. Cumulative spectral decay graph for the receiver location B1.

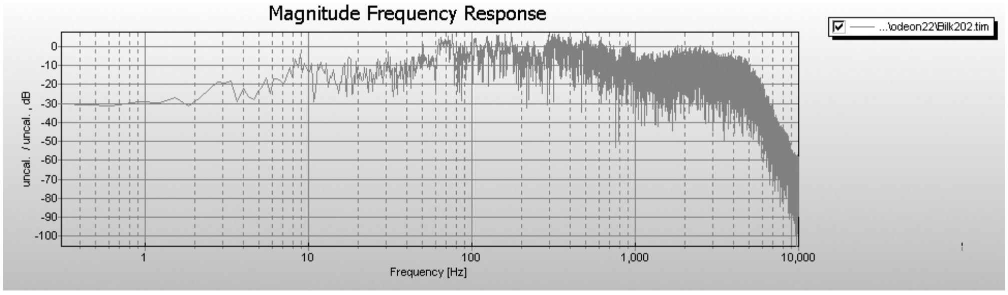

Figure 194. Magnitude frequency response graph for the receiver location B2.

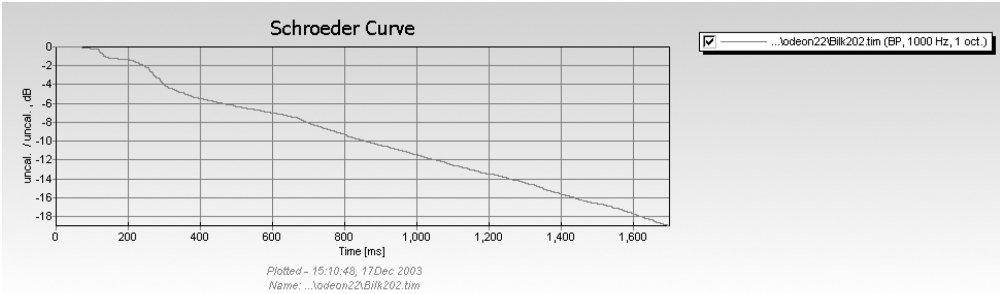

Figure 195. Schroeder curve for the receiver location B2.

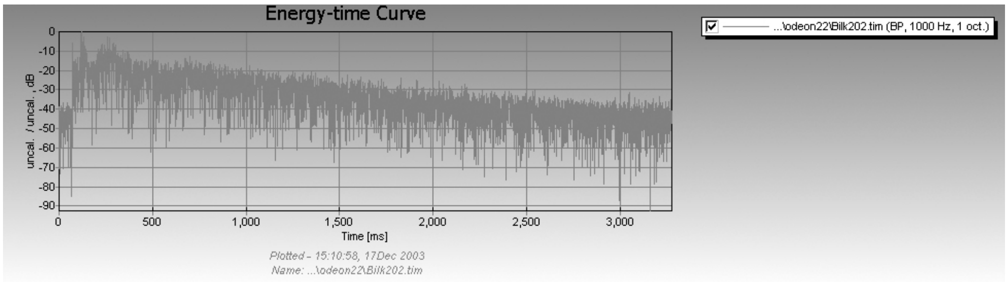

Figure 196. Energy-time curve for the receiver location B2.

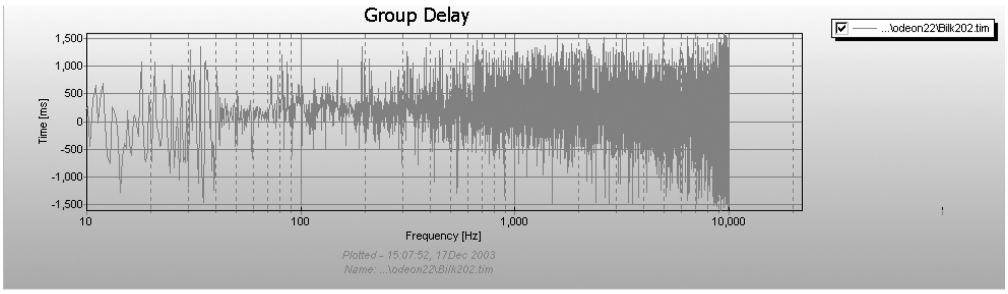

Figure 197. Group delay graph for the receiver location B2.

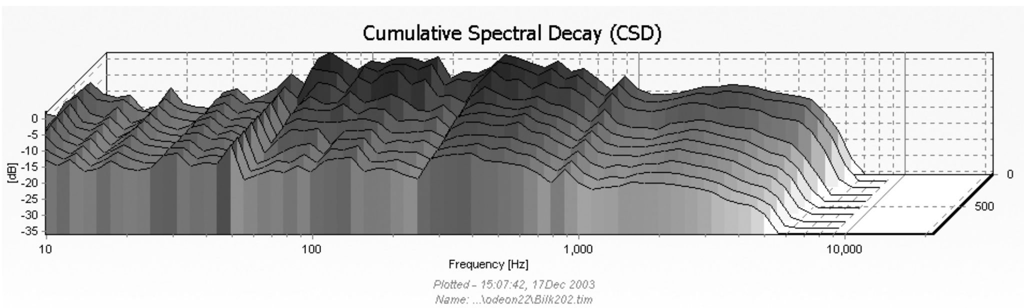

Figure 198. Cumulative spectral decay graph for the receiver location B2.

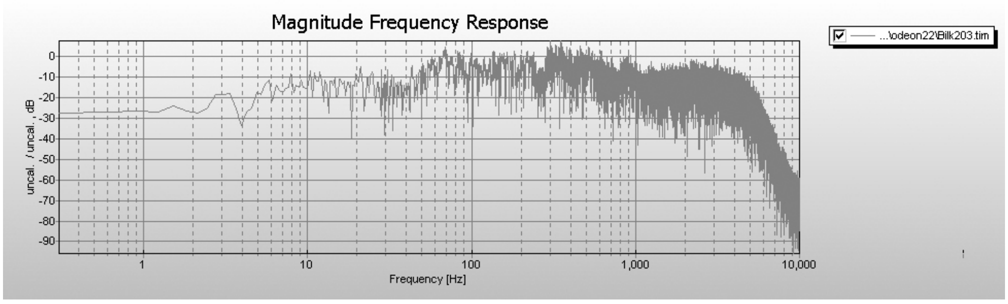

Figure 199. Magnitude frequency response graph for the receiver location B3.

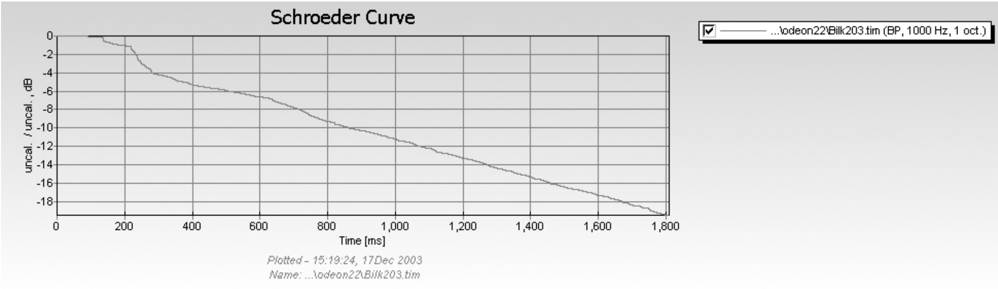

Figure 200. Schroeder curve for the receiver location B3.

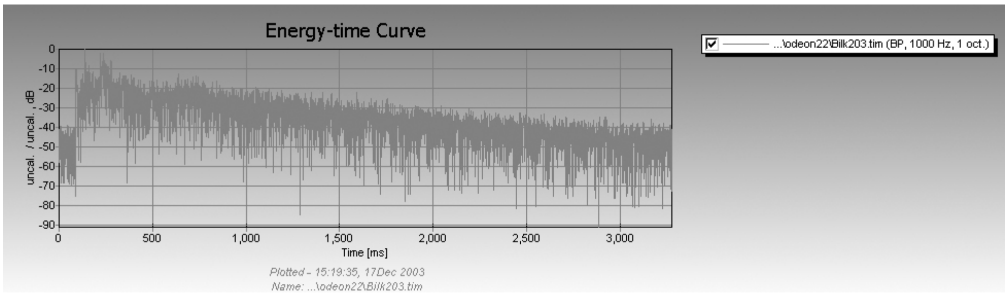

Figure 201. Energy-time curve for the receiver location B3.

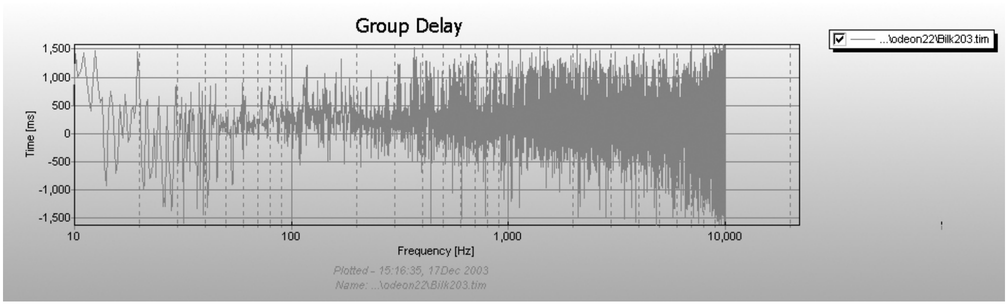

Figure 202. Group delay graph for the receiver location B3.

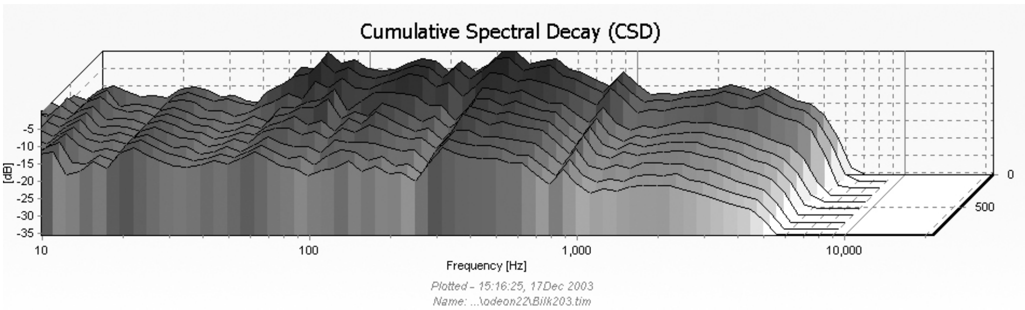

Figure 203. Cumulative spectral decay graph for the receiver location B3.

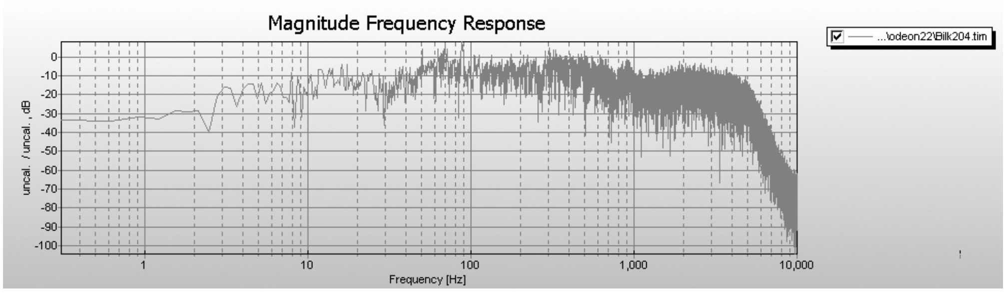

Figure 204. Magnitude frequency response graph for the receiver location B4.

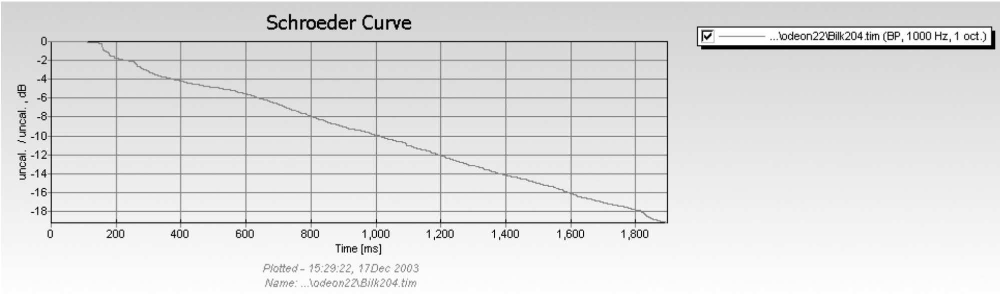

Figure 205. Schroeder curve for the receiver location B4.

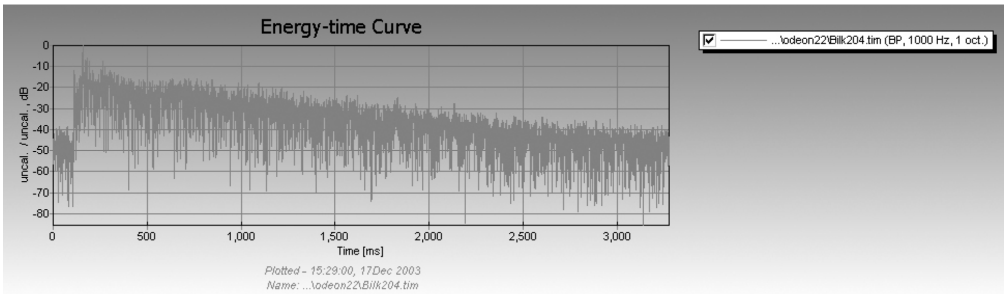

Figure 206. Energy-time curve for the receiver location B4.

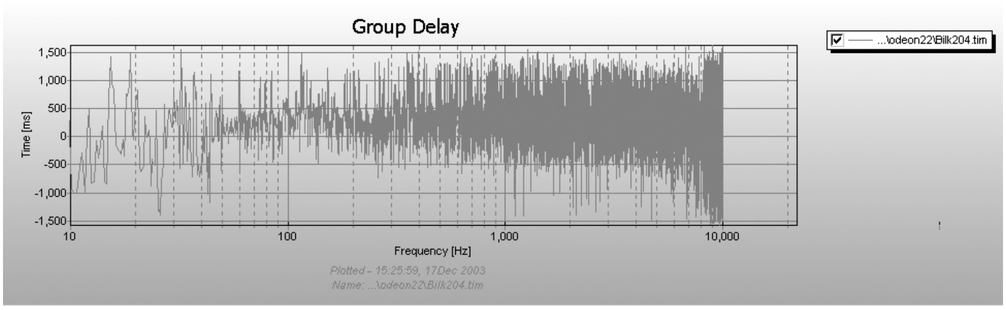

Figure 207. Group delay graph for the receiver location B4.

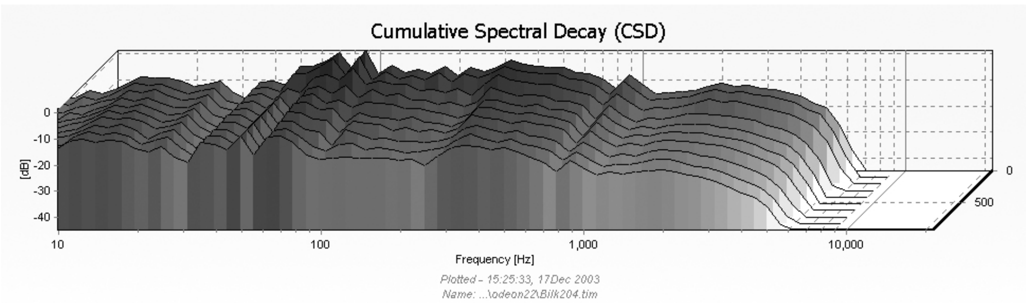

Figure 208. Cumulative spectral decay graph for the receiver location B4.

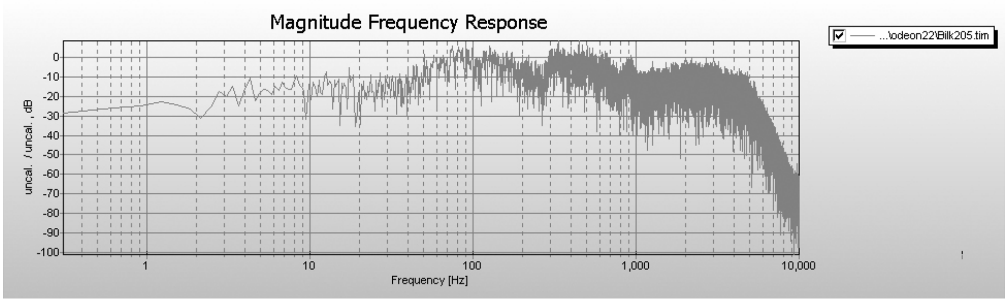

Figure 209. Magnitude frequency response graph for the receiver location B5.

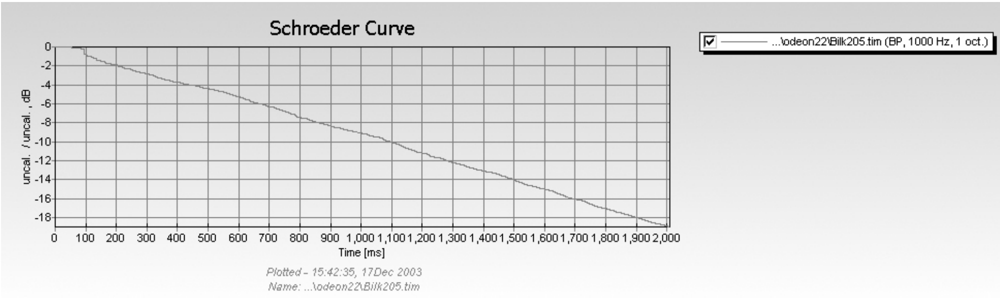

Figure 210. Schroeder curve for the receiver location B5.

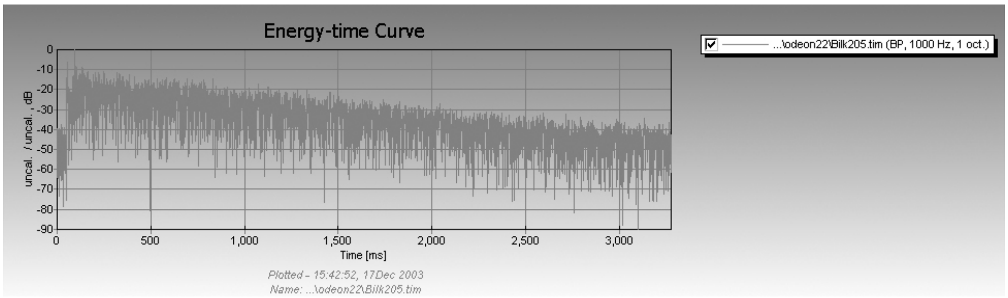

Figure 211. Energy-time curve for the receiver location B5.

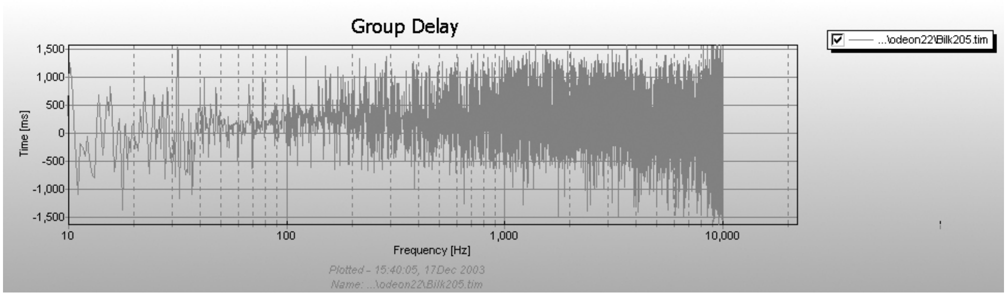

Figure 212. Group delay graph for the receiver location B5.

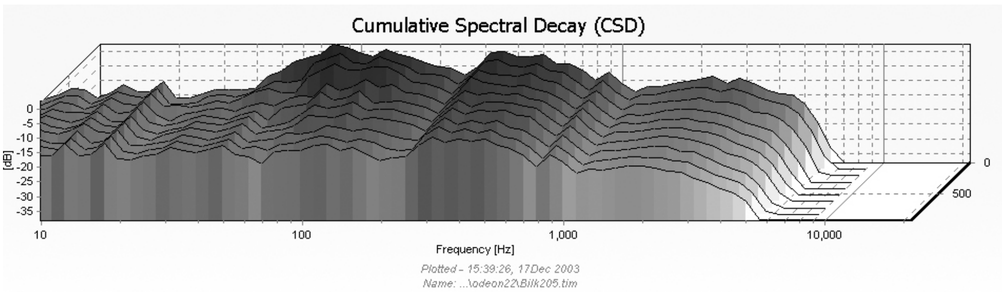

Figure 213. Cumulative spectral decay graph for the receiver location B5.

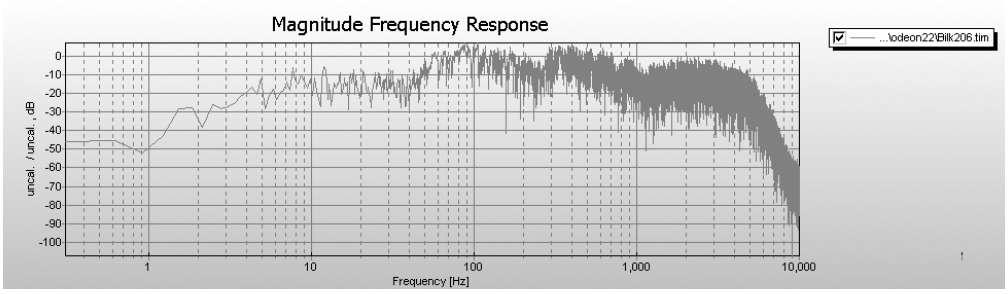

Figure 214. Magnitude frequency response graph for the receiver location B6.

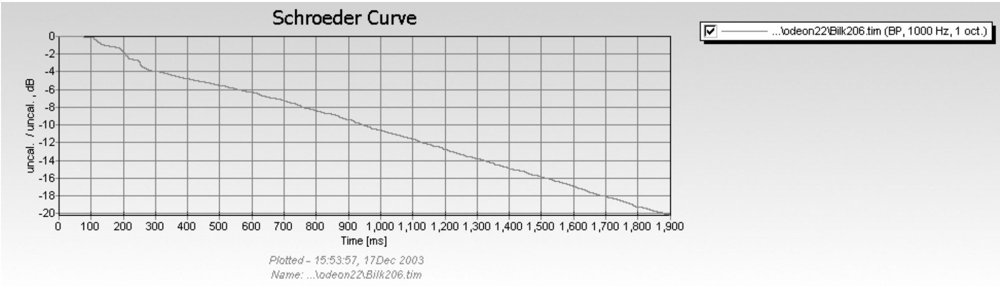

Figure 215. Schroeder curve for the receiver location B6.

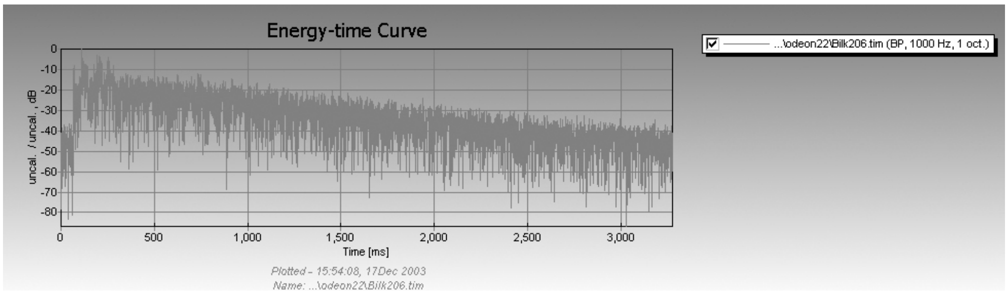

Figure 216. Energy-time curve for the receiver location B6.

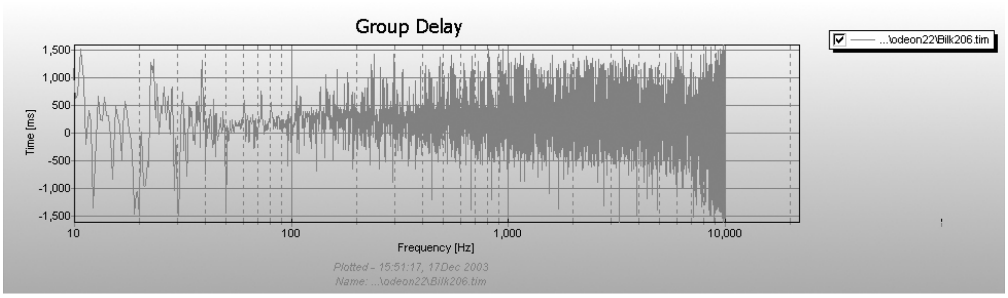

Figure 217. Group delay graph for the receiver location B6.

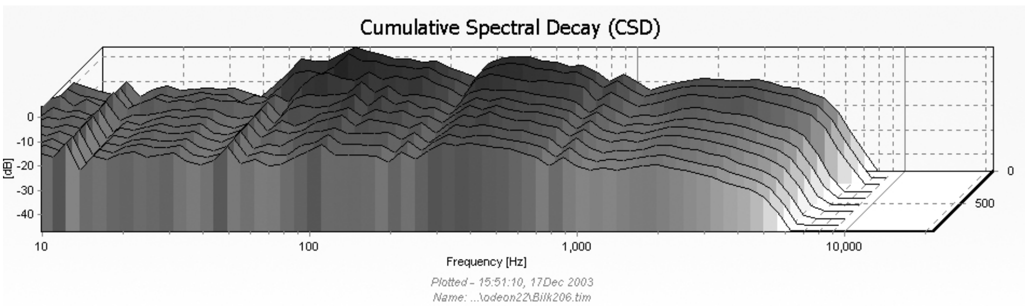

Figure 218. Cumulative spectral decay graph for the receiver location B6.

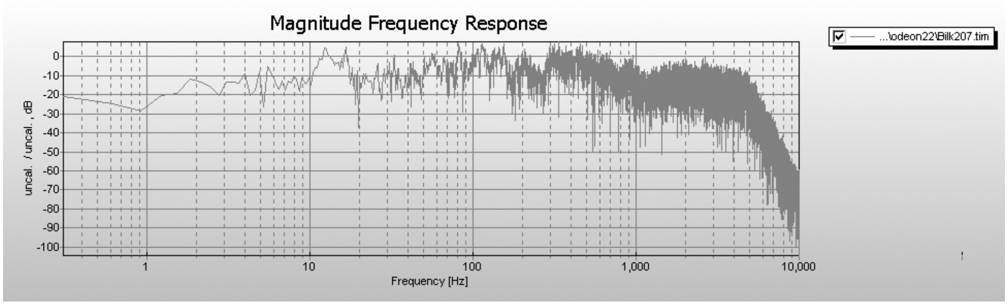

Figure 219. Magnitude frequency response graph for the receiver location B7.

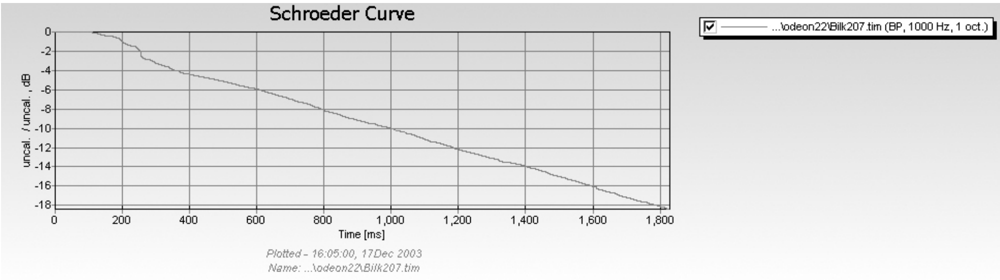

Figure 220. Schroeder curve for the receiver location B7.

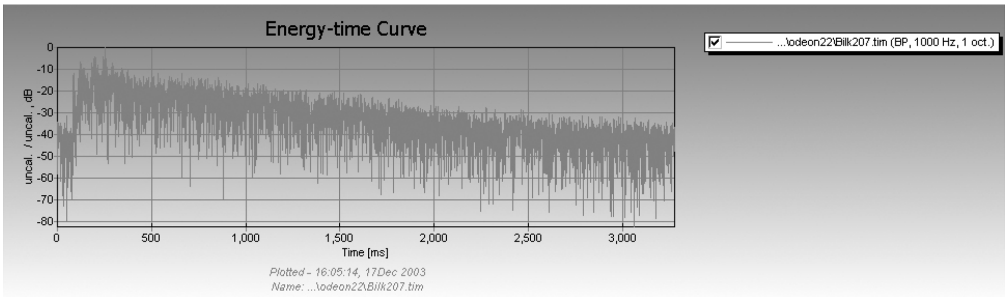

Figure 221. Energy-time curve for the receiver location B7.

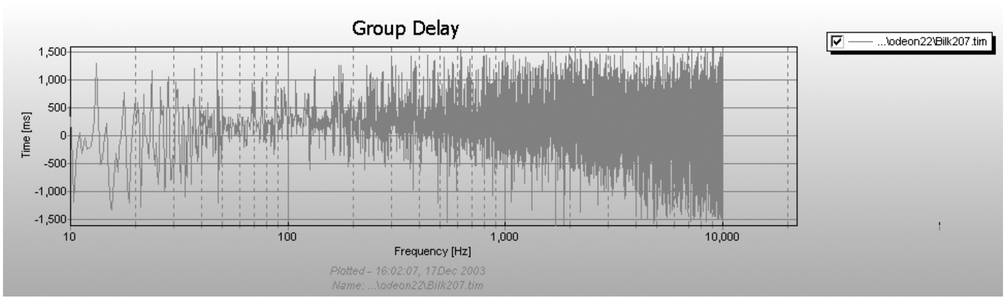

Figure 222. Group delay graph for the receiver location B7.

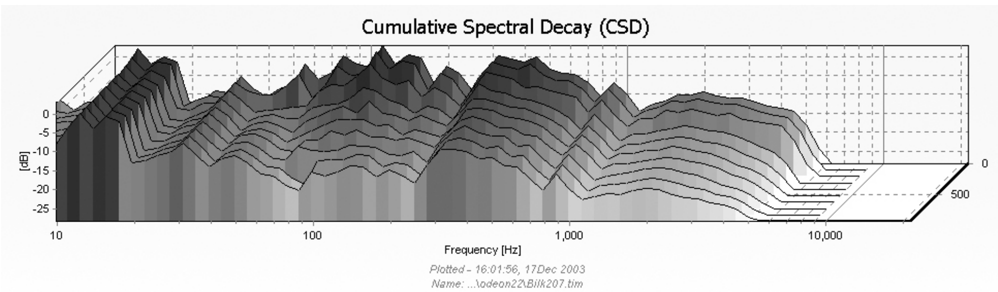

Figure 223. Cumulative spectral decay graph for the receiver location B7.

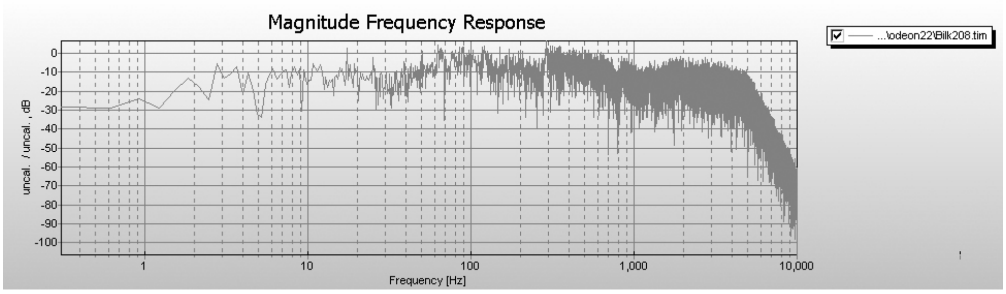

Figure 224. Magnitude frequency response graph for the receiver location B8.

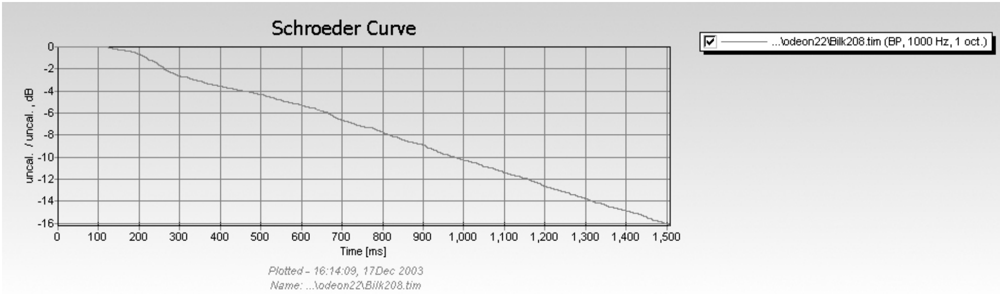

Figure 225. Schroeder curve for the receiver location B8.

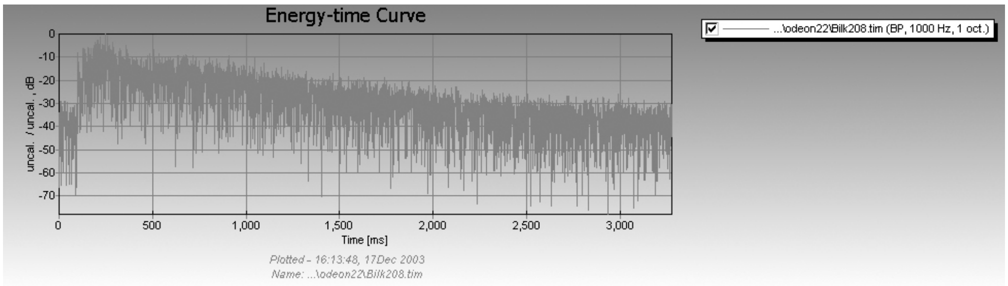

Figure 226. Energy-time curve for the receiver location B8.

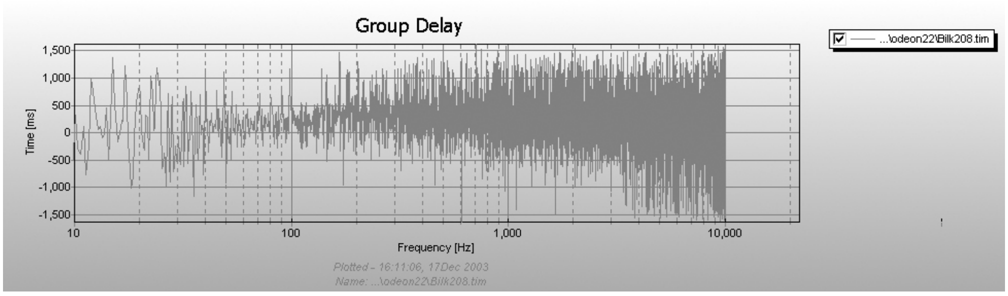

Figure 227. Group delay graph for the receiver location B8.

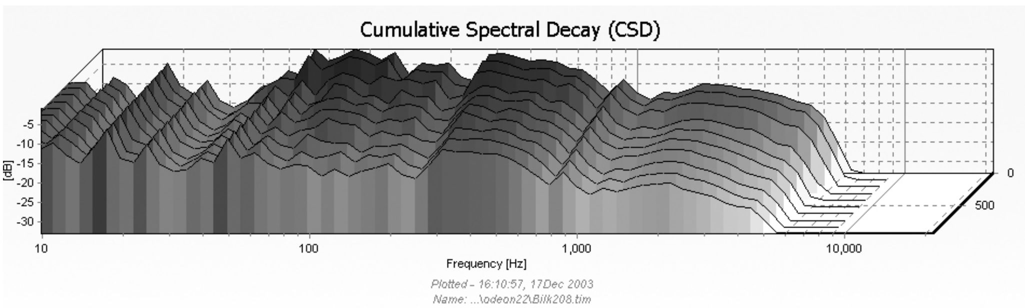

Figure 228. Cumulative spectral decay graph for the receiver location B8.

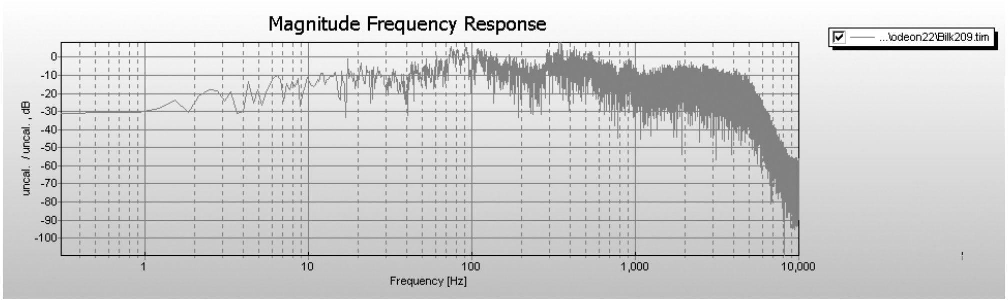

Figure 229. Magnitude frequency response graph for the receiver location B9.

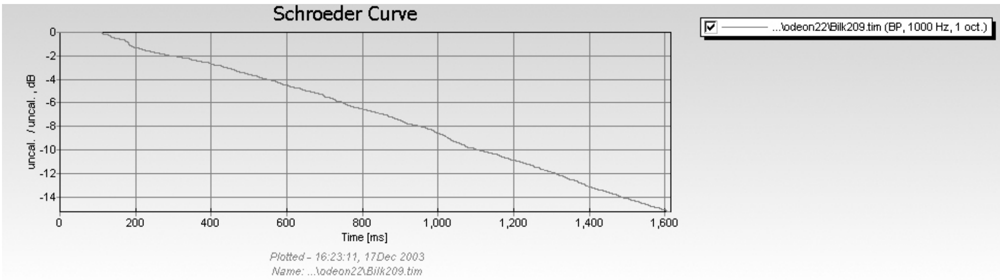

Figure 230. Schroeder curve for the receiver location B9.

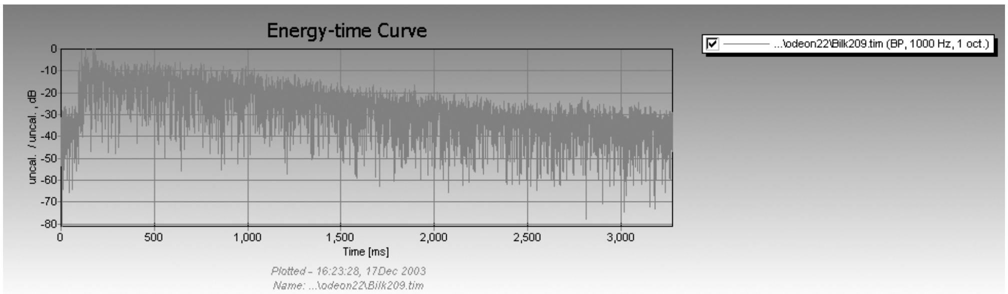

Figure 231. Energy-time curve for the receiver location B9.

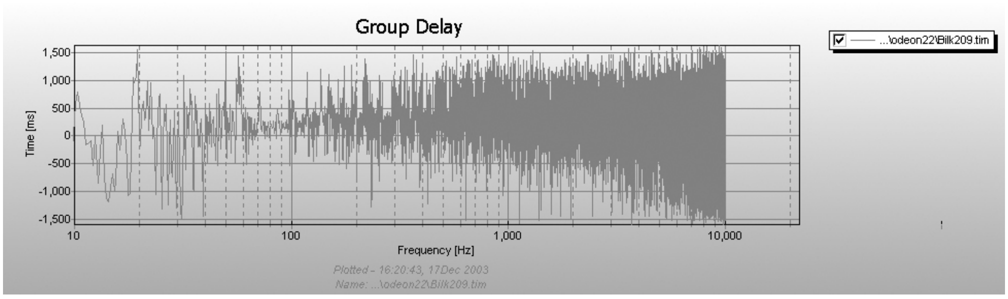

Figure 232. Group delay graph for the receiver location B9.

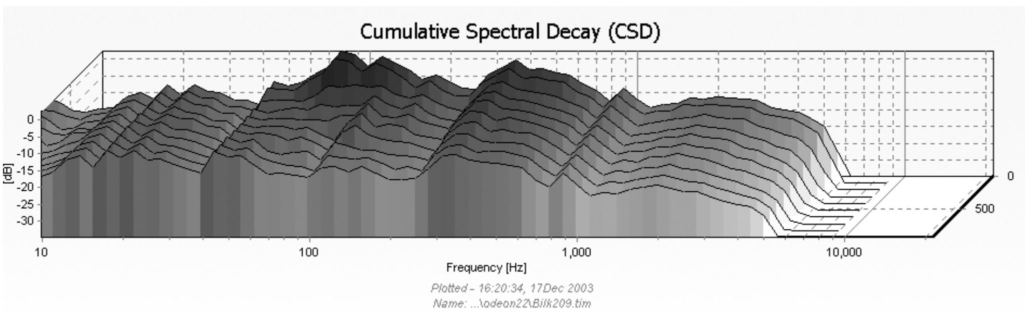

Figure 233. Cumulative spectral decay graph for the receiver location B9.

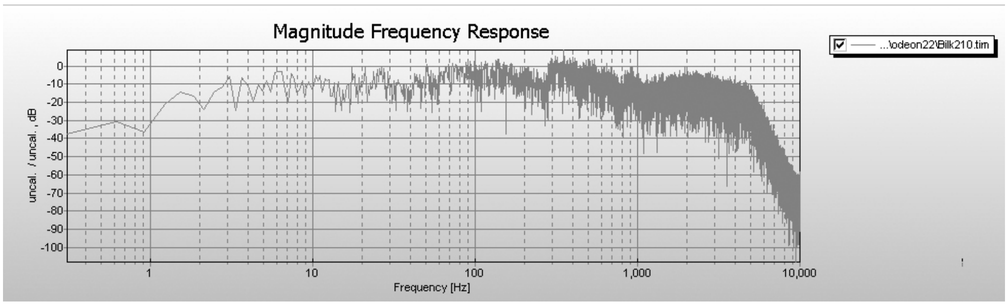

Figure 234. Magnitude frequency response graph for the receiver location B10.

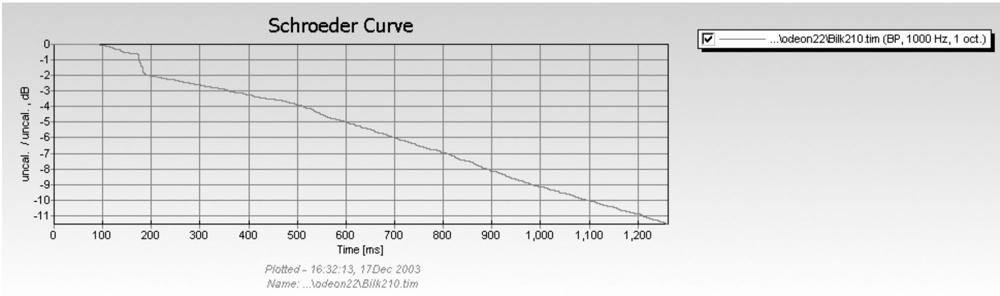

Figure 235. Schroeder curve for the receiver location B10.

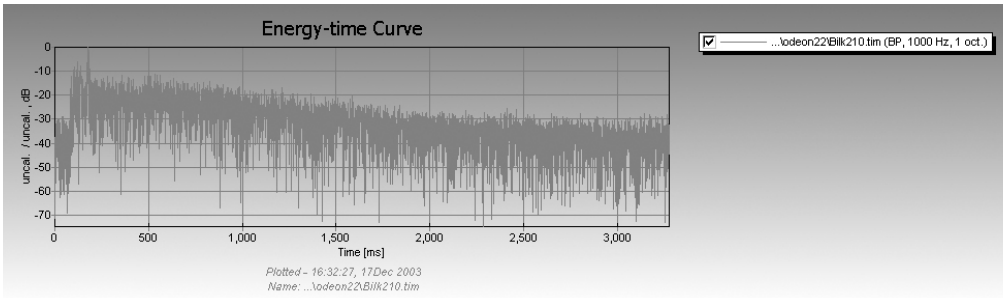

Figure 236. Energy-time curve for the receiver location B10.

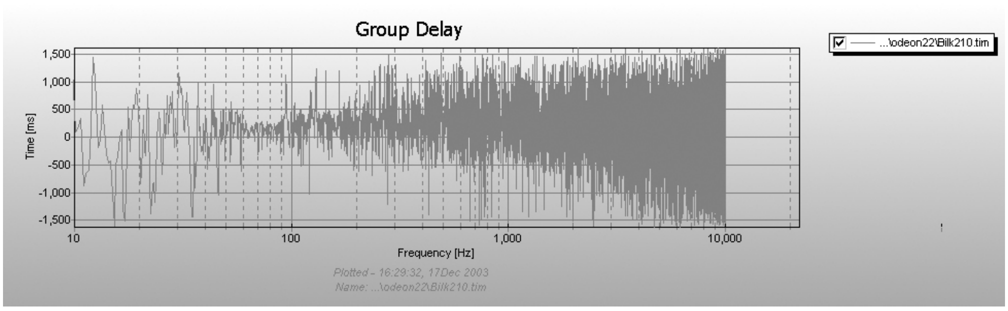

Figure 237. Group delay graph for the receiver location B10.

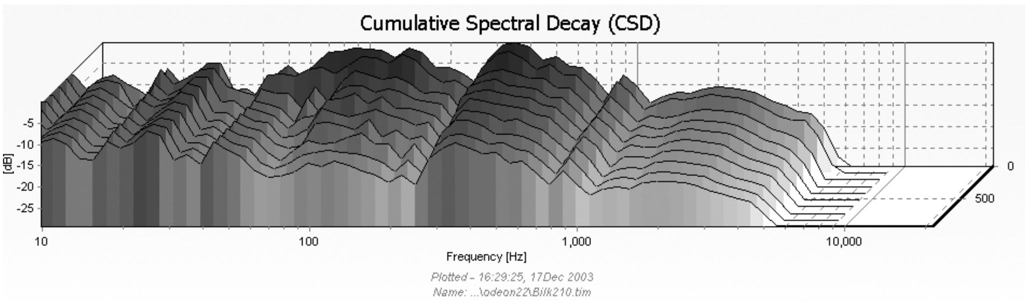

Figure 238. Cumulative spectral decay graph for the receiver location B10.

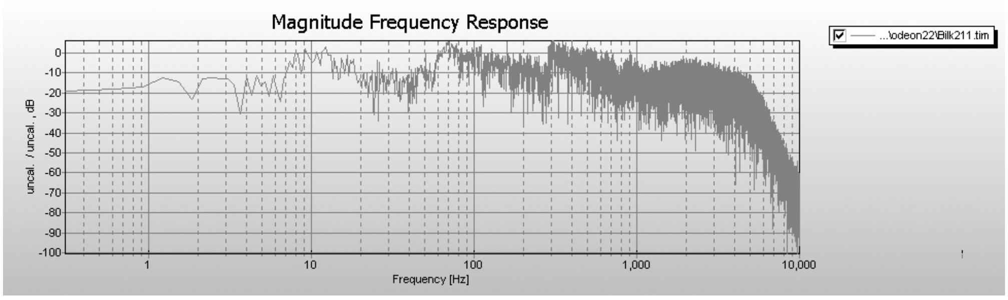

Figure 239. Magnitude frequency response graph for the receiver location B11.

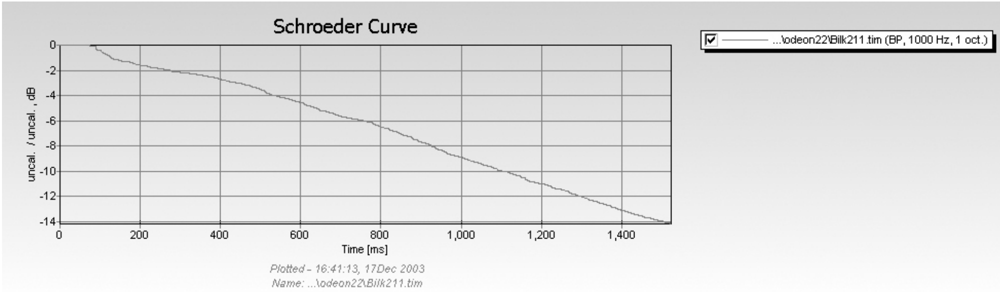

Figure 240. Schroeder curve for the receiver location B11.

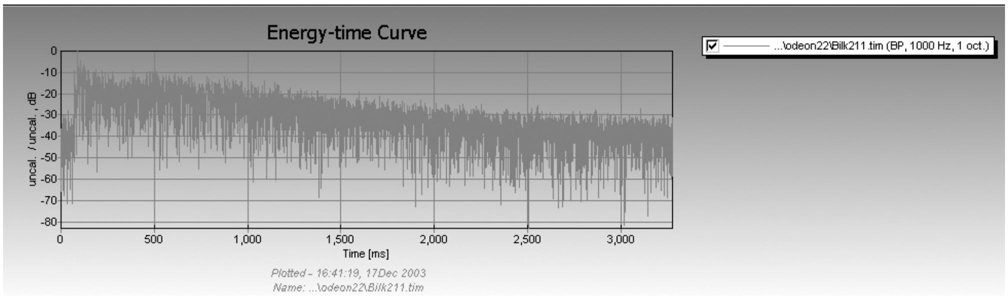

Figure 241. Energy-time curve for the receiver location B11.

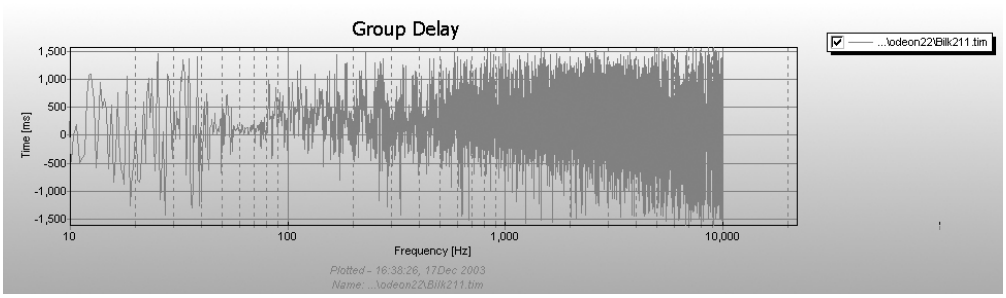

Figure 242. Group delay graph for the receiver location B11.

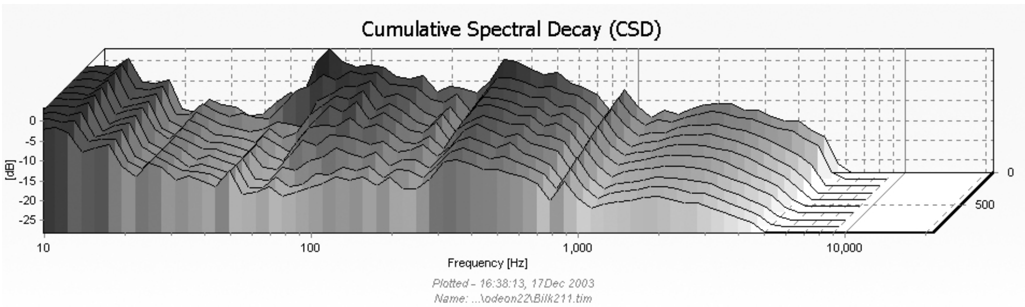

Figure 243. Cumulative spectral decay graph for the receiver location B11.