DIFFUSIVITY OF PERFORMANCE SPACES
- ITS SIGNIFICANCE TO PERCEIVED SOUND QUALITY FROM DIRECTIVE SOURCES

Magne Skålevik

www.akutek.info
and
Brekke & Strand Akustikk
Hovfaret 17
0275 Oslo, Norway
msk@bs-akustikk.no

ABSTRACT

It is widely recognised that music and speech sources are not only directive and frequency dependant, the spatial and spectral radiation pattern changes rapidly and randomly with time. Performance spaces of different acoustical condition have been analysed in 6 virtual channels with room acoustical simulation software. A source of random radiation varying with time and direction has been simulated and used as input in the simulated room acoustical channels. The free-field direct components from a time varying directional source correlates poorly with the total (omni-equivalent) energy produced. Rooms of adequate size can provide reliable early sound transmission that compensates for the shortcomings of the direct component. E50 is defined as received energy within 50ms after first arrival of sound, and the simulations shows that E50 correlates highly with sound energy produced by the source, and significantly better than the free-field condition. Excess sound absorption and room size proves to be the most prominent threats to the correlation between received early sound and produced sound. As long as rooms are small, sufficient early sound seems to be guaranteed irrespective of the distribution of surface absorption and scattering. This is significant to rehearsal rooms, but also when considering size in concert hall design. Dependence of size can be explained by image sources in image rooms, in an image space containing the real room. The significance of surface scattering must be investigated with even more directive sources than applied in this study so far, in order to predict the effect of a sound beam hitting only a part of a wall, ceiling or floor. Diffusivity and its temporal, spectral and spatial domain are discussed by theses and antitheses. The term diffusivity includes the room acoustic property that contributes to smooth out and compensate for negative effects of directive sources.

1. INTRODUCTION

The directivity of musical sources and its significance to in performance spaces has been extensively explored since the 1960's by several authors, especially so by Meyer, who in 1972 [1] reported from measurements on string instruments, showing that the direct sound intensity from the instruments depends strongly on direction and frequency. Meyer suggested improvements to orchestra layout, taking instrument's orientation into account, in order to optimize the quality of the direct sound received by the audience. His work has later been extended to include more instruments, showing similar properties.

More recently Vigeant, Wang and Rindel [2] have studied the importance of the directional patterns of sources used in computer models, concluding that predictions and auralizations can be improved by taking some proper directional pattern into account. The authors concluded that it is important to consider source directivity when using computer modelling. Rindel and Otondo [3] have utilized multi-channel room acoustical techniques in order to achieve better auralizations, taking the temporally changing directionality of musical instruments into account.

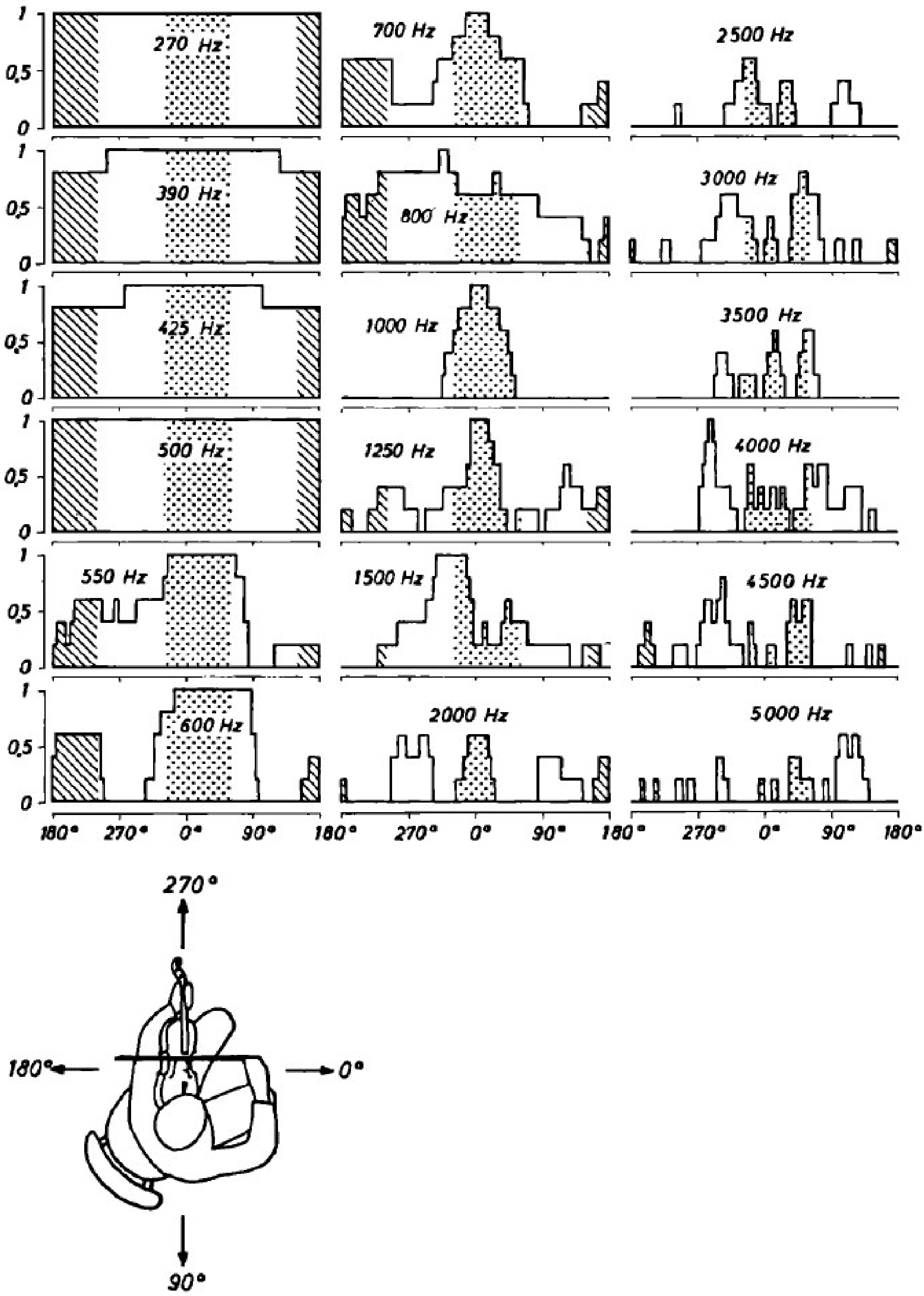
It can be presumed that direct sound from most performance sources (musical instruments and human voice) depends on direction and frequency, and therefore on position and orientation of the instrument relative to the listener's ear. However, it is evident that the directional pattern also changes from one note to another, and even when the same note is played with vibrato or played on different strings, positions or settings of one and the same instrument. For example, Weinreich [4] (1996) stated that the radiation pattern of string instruments can vary drastically within very small musical intervals. Moreover, the pattern of hand held instruments or human voice will change orientation continuously with the performer's movements.

Our current research is, in common with the investigations above, based on the importance of considering the directivity of performance sources. In contrast however, we shall focus on how room acoustical properties can reduce the unwanted effects on sound quality from unreliable direct sound radiation.

This paper is a report on findings in our research so far

2. DIRECT SOUND FROM A VIOLIN

We shall start with a brief conclusion on some important consequences of the early work by Meyer (1972). *Figur 1* shows the probability of receiving maximum direct sound level from violins, at different angles and frequencies, and illustrates the risk of lacking mid-high frequency content for receivers at any seat. Moreover, the steep steps of the diagram indicates that the direct sound spectra will be very different for two listeners in the same audience, and that for each listener, spectral components in the direct sound will have a random-like on-off behaviour even for small movements by the musician. Similar properties apply to other instruments that have been investigated by anechoic measurements. Meyer has continued the investigations over the last decades [5], [6].



Figur 1: Probability of receiving maximum direct sound level from violins, at different angles and frequencies (After Meyer, 1972), illustrating the unreliability in quality of direct sound.

3. TWENTY-FOUR REMARKS ON DIRECTIVITY IN REVERBERANT SPACES

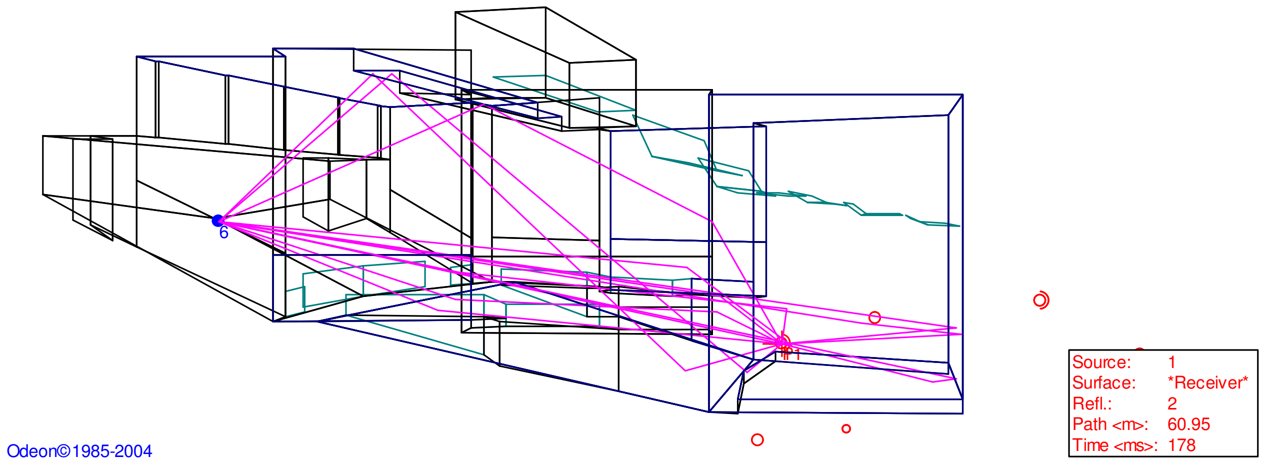
3.1. Direct sound properties

In this section it is deduced that the direct sound from a performance source is not a reliable carrier of sound of preferred quality.

1) *Direct sound* radiated from a performance source (musical instrument or human voice) varies with angle, frequency and time in a random-like manner
2) At given time and frequency, the radiation pattern can be described by a polar diagram
3) At given time and angle, the frequency distribution can be described by a spectrum
4) At given time, the received direct sound spectrum is unique to each listener, e.g. it deviates more or less from the average over the group of listeners
5) The direct sound quality received by each listener is generally different from the direct sound quality at the musician's ears
6) The time-dependency is due to the sequence of micro-events in the performance, e.g. musical notes, spoken words, and the performers movements
7) *Spectral fullness* of sound from an instrument is associated with the quality of its power spectrum
8) The direct sound path from a non-omni-directional source can generally not be relied upon as a carrier of the spectral fullness of sound, as follows per definitions of omni-directionality and spectral fullness
9) Non-reverberant spaces are associated with poor sound transmission quality, as is to be expected from the above, since pure direct sound is not reliable for providing sound transmission of preferred quality

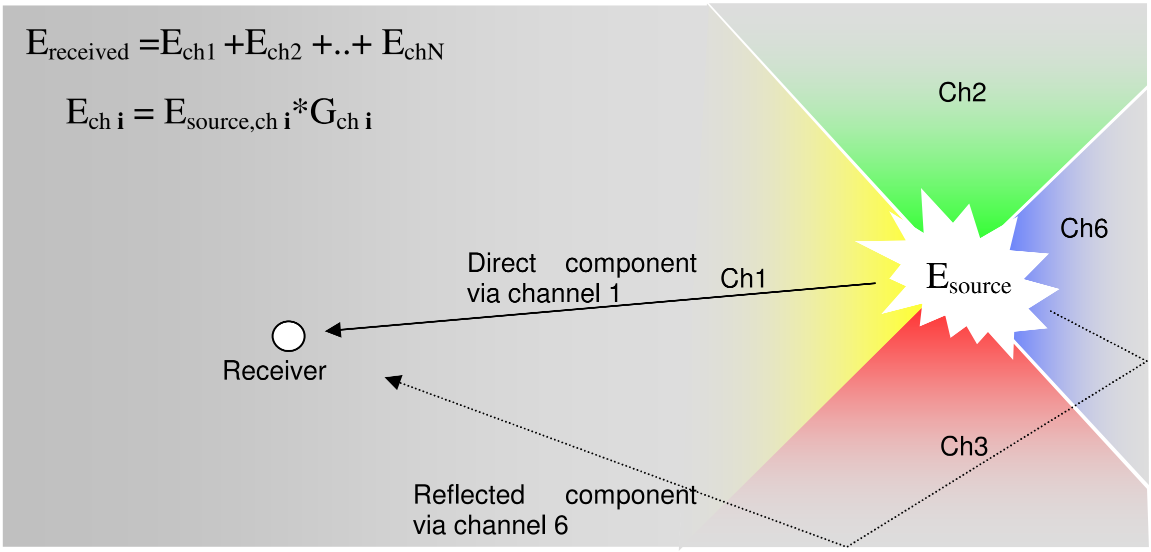
3.2. Sound transmission in reverberant spaces

10) In a reverberant space there are an endless number of paths that connects source and receiver, see *Figur 2.*

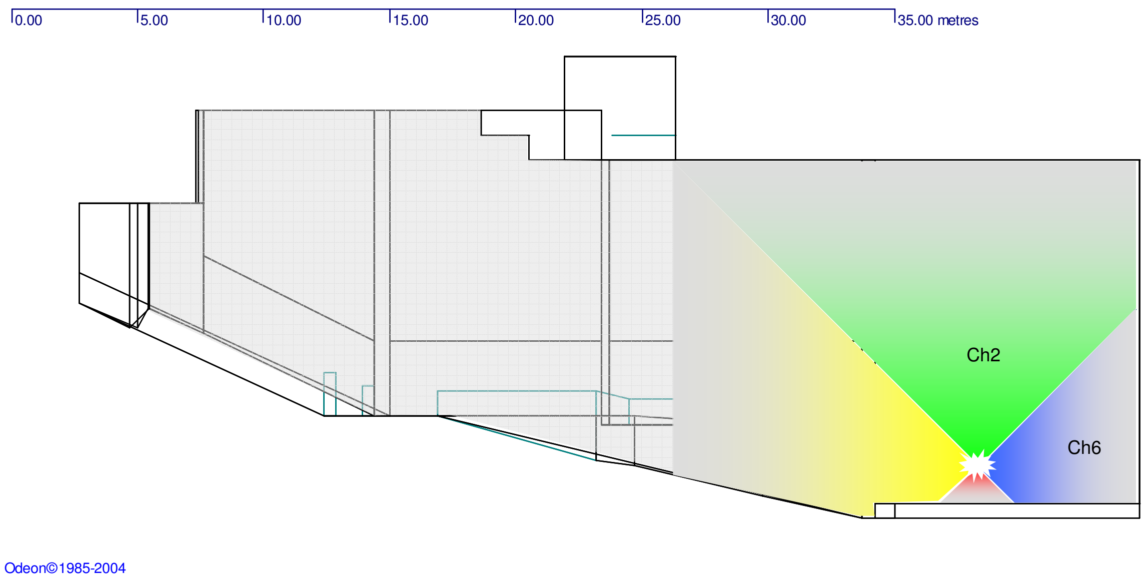


Figur 2: Some of the transmission paths connecting source and receiver in Elmia concert hall

11) The sound transmission from source to receiver in a reverberant performance space can be analyzed as the re-integration of partial sound channels in all directions out from the source, and computed as a sum of the discretion of such channels, each channel having properties that can be described with room acoustical energy parameters, or signal processing terms like transfer function, impulse response, etc., see *Figur 3*.



Figur 3 Energy transmission from a performance source event via N room acoustic channels to a receiver in a reverberant space. The input $E_{source,ch\,i}$ from the source into cannel i is the direct (free field) radiation in direction i and it varies randomly. The example shows 4 of the total 6 channels, as applied to computer simulations in the Elmia Concert Hall (below).



12) The sound transmission channels 10) can be used in auralizations by feeding multi-channel anechoic recordings into the sound transmission channels, e.g. by convolving each record-channel with respective transmission channel BRIR, before mixing and reproducing sound in headphones or loudspeakers. This has been looked into by Rindel and Otondo [3].
13) The abundance and individual properties of the paths 10) is significant to the sound quality of the sound transmission from source to receiver in a performance space
14) Listeners and performer prefer spectral fullness from the instruments in both early and late sound portions, however high frequency attenuation and sometimes low frequency boost is preferred
15) The acoustic properties of a performance space can make a significant difference to perceived sound quality
16) The larger the performance space, the more the sound quality depends on design, especially so for early sound quality
17) Listeners and performers prefer *temporal evenness* of the sound transmission, in contrast to disliked echoes and empty time-gaps
18) *Spatial evenness* is associated with spatially evenly distributed sound transmission paths as seen by the source and the receiver
19) Spatial evenness depends on even reflection properties of nearby surfaces as seen by source and receiver
20) Spatial evenness is preferred by listeners and performers
21) Spatial evenness of late reverberant sound (>80ms) is often recognized as envelopment
22) Spatial evenness of early sound (<80ms) provides wideness, often referred to as apparent source width ASW, but in the ideal condition also with absence of false localization and or an apparent hole in the middle of the sound image
23) Abundance[1] of transmission paths, spatial evenness, spectral fullness and temporal evenness are all constituting the property of a performance space that can be recognized as DIFFUSIVITY
24) Diffusivity in its widest sense is essential for the perceived sound quality in a performance space, since the more diffuse transmission system suppresses the randomness of the direct sound input from performance sources

4. DIFFUSIVITY – THESES AND ANTITHESES

In the matrix below, the concept of diffusivity is discussed by theses and antitheses. The transition time T_t is here defined as the time relative to arrival of direct sound, after which the receiver is evenly surrounded by the spectral fullness of the source. It is not to be confused with the initial time delay gap ITDG, which only depends of the time of the first reflection. The time interval before T_t is dominated by the randomness of direct sound and early reflections, and should be small compared with 50ms. After T_t, the received sound is in what we may call the saturation state.

Domain	Diffuse	Non-diffuse
Spatial	Diffuse sound field	Free field
	Reverberant sound	Anechoic sound
	Insensitive to source directionality	Sensitive to source directionality
	Even SPL distribution in receiver area	Hot spots and cold spots in the receiver plane
	Receiver is evenly enveloped by sound	Sound is received from prominent directions

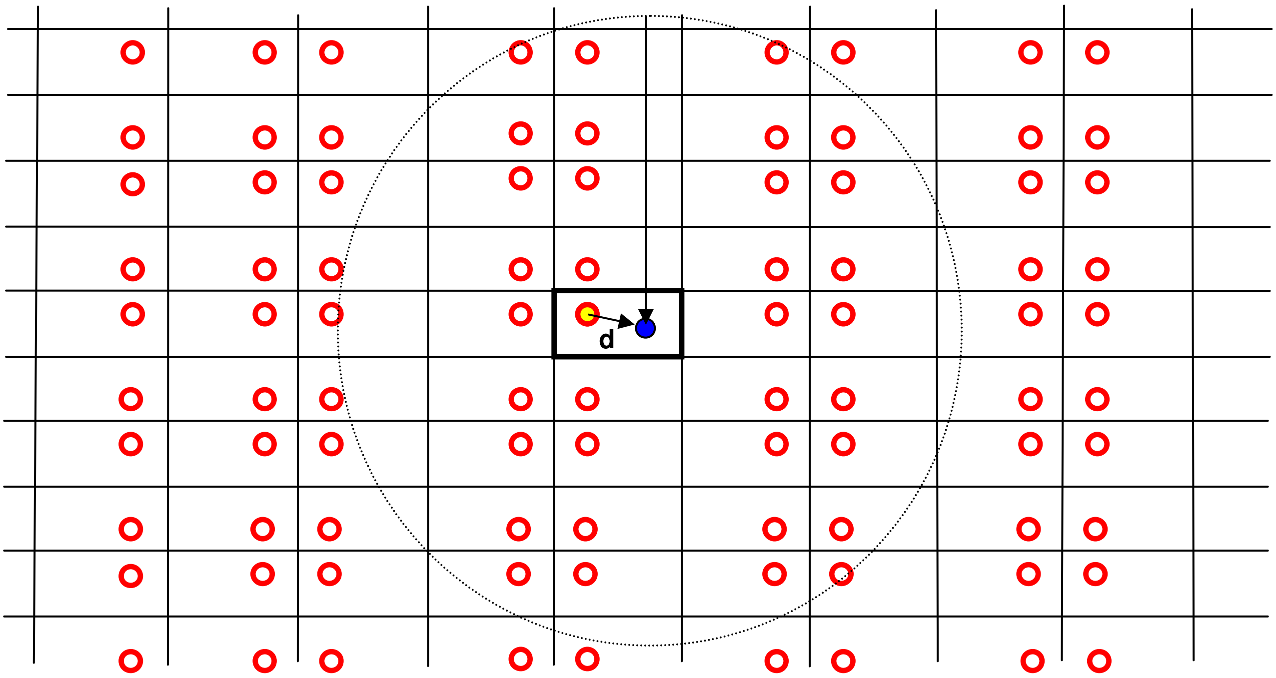
[1] This is equivalent to so called diversity technique or multiple band technique applied in wireless communication systems to improve reliability of transmission

Domain	Diffuse	Non-diffuse
Spatial	No sound shadows	Sound shadows
	No acoustic glare	Acoustic glare
	Diffuse reflections	Prominent specular reflections
	Mat paint surfaces (optic analogy)	Mirrors (optic analogy)
	Even broadening of sound image	False localization
	Small or modulated surfaces	Large plane surfaces
	Abundance of transmission paths	Few and strong transmission paths
	Surfaces close to source and receiver	Surfaces distant from source and receiver
	Short TT	Long TT
	Absorption is evenly distributed	Lumped absorption
	No parallel surfaces	Large plane, parallel surfaces
	Short ray paths	Long free ray paths
Spectral	Even surface-absorption spectra	Uneven surface-absorption spectra
	Broadband reflections	Narrowband reflections
	Spectral quality not sensitive to directivity	Source directivity reduces spectral quality
	No comb-filter effects	Comb-filter effects
	Pleasant timbre	Unpleasant timbre, harsh or boxy sound
	High mode density	Prominent modes, boomy sound
	Even spectra	Peaks and dips in spectra
Temporal	No echoes or prominent single reflections	Echoes, flutter-echoes, prominent single reflections
	Temporal distribution not sensitive to source directivity	Directive sources may cause echoes
	No energy-time gaps	Energy-time gaps
	Smooth exponential decay	Double slopes or uneven decay
	Even distribution in impulse response	Peaks and tips in impulse responses
Room acoustical channel processing	Crosstalk between channels is high	Channel separation is high
	Transmission Loss approaches zero in all channels in the 100% diffuse room case	Transmission Loss is far from zero, approaches infinity channels not containing the direct sound path between source and receiver in the pure free-field case
	Transmission Loss are equal in all channels in the 100% diffuse room case	Transmission Loss differ between channels in the pure free-field case
	High correlation between source sum signal and received sum signal	Low correlation between source sum signal and received sum signal

5. DIFFUSIVITY DUE TO ROOM SIZE

In this section we shall study the diffusivity effect due to room volume size only, keeping the effects of scattering surfaces and irregularities out of consideration. Given a simple parallelepiped (i.e. a room with rectangular sections) of dimension X*Y*Z, with perfectly reflecting, non-scattering surfaces forming 3 parallel pairs.

The optical analogy of a mirror room can be useful in order to illustrate how an observer inside the room containing a source will receive multiple reflections that appear to come from multiple image sources in multiple adjacent image rooms of identical volume v=X*Y*Z, forming an image space, see *Figur 4*. Each one of the image sources appears to give an impulse as an echo of the real source. The echo arrives at the time t after the impulse left the real source, and it appears to come from a distance c*t from the receiver, c being the speed of sound. During the period from t=0 to t=t, the observer will have received echoes from image sources at distance less than R=c·t from the receiver. This is the apparent radius of the image space at time t.



Figur 4: 2-D section through the image room space. Each image room contains one source, and the number of image sources N is determined by the number of rooms of volume v contained by the sphere within the radius of R=c·t.

The volume of the image space at time t is V= ¾π ·$(c\cdot t)^3$ and it contains the time-dependent number of image sources N(t), which at the time t=t is

$$N(t) = 4\pi/3 \cdot (c\cdot t)^3/v$$

Given that the energy E from the real source is somehow concentrated to one or more beams of random direction with the total solid angle (=spherical area at 1m from source) Ω =4π/D, where D is the directivity. After time t, the receiver will be surrounded by N(t) image sources. As N(t) increases with time, the chances for the receiver being hit by one or more beams increase correspondingly.

By the time N(t) reaches the value of D, there are enough beams to cover all directions, since the total solid angle reaches N(t)·Ω=4π. The average observer will then have been hit by an energy quantum equivalent to a hit by the beam from one image source, regardless of source directionality. This time is the transition time t= T_t, mentioned above. After T_t, the average observer will be hit by more than one image source, and very soon the receiver will be able to perceive envelopment of sound. T_t is also the transition to the condition where statistical energy analysis applies. For a source with effective beam of directivity D inside a room of volume v, the transition time is

$$T_t < 1/c \cdot [3v \cdot D/(4\pi)]^{1/3} \approx 0.0018 \cdot (v \cdot D)^{1/3}$$

Example: If a source with directivity range D=10-40 is inside a rehearsal room of v=5*4*3=60m^3, the transition time will be in the range of T_t= 15-24ms, while for the same source within a double-cube concert hall of v=42*21*18=16.000m^3, the transition time will be in the range of T_t= 99-157ms. It is evident that the rehearsal room will provide early energy from the source quite independent of directionality due to its smaller volume, while this is not the case in the large concert hall. By the time $2 \cdot T_t$ the probable number of hits from surrounding image sources has increased to 2^3=8, which results in envelopment for the average receiver in the rehearsal room from the time 30-48ms, again due to limited size, only. In the concert hall the similar time for probable envelopment onset due to volume is 100-300ms. In comparison, the time it takes for sound to complete loop travel along the diagonal of the room is 42ms and 300ms, respectively.

The chance of being hit by a direct beam from the real source to the receiver is 1/D, and the energy at distance d would in that case be $E/(\Omega d^2)$. Compared to this, the average observer will by the time T_t have received an early energy quantum of at least $E/[\Omega\ (c \cdot T_t)^2]$ anyway, regardless of the probability of a direct hit. If the transition time is short, this early energy "guarantee" will be adequately strong, and if also the transition time is T_t<50ms, the listener will take advantage of the perceived merging of separate energy components that arrives within the 50ms interval. This is important since practical sources do not have single beams, so the energy quantum will be received as an integral of beamlets from several image sources. However this does not increase the chance for a direct hit to more than 1/D.

On the other hand, the probability of not being hit by a direct beam from the real source is 1-1/D, which is between 90% and 98% whenever directivity is in the range of D=10-50 (Directivity index DI=10-17dB). In the case of no beam hit, there will in practice be some residual radiation outside the main beam, but there is no theoretical lower limit level for the direct component of such residual radiation. E.g. in the symmetry plane of a dipole the level approaches minus infinity. If the residual radiation is $k \cdot E_0$ is not hit by a beam from any image source, then it must be hit by residual energy from N(t) image sources, which may accumulate to a considerable amount of energy, but limited within the energy density $\varepsilon = k \cdot E_0/v$. If k is very small, the residual energy will have negligible effect, but if k is considerable, this may result in a shorter transition time than the volume and directivity dependent T_t above.

In this section we have shown that room size is significant to the sensitivity towards directionality of sources. Surface scattering is not taken into account. Smaller volumes provide for diffusivity and suppress the effect of unreliable direct sound from directive sources more effectively than does the large volumes. This does not necessarily mean that surface scattering is not significant to rehearsal room quality, e.g. to attenuate acoustic glare and prominent single reflections.

6. COMPUTER SIMULATION

The time-energy-frequency pattern produced by a performance source is an important property of its signature. Above we have pointed at the unreliability of the direct (free field) component as a carrier of this signature. We shall now look to the early reflected energy and explore see how it correlates to the source energy, and how this is affected by the acoustic environment.

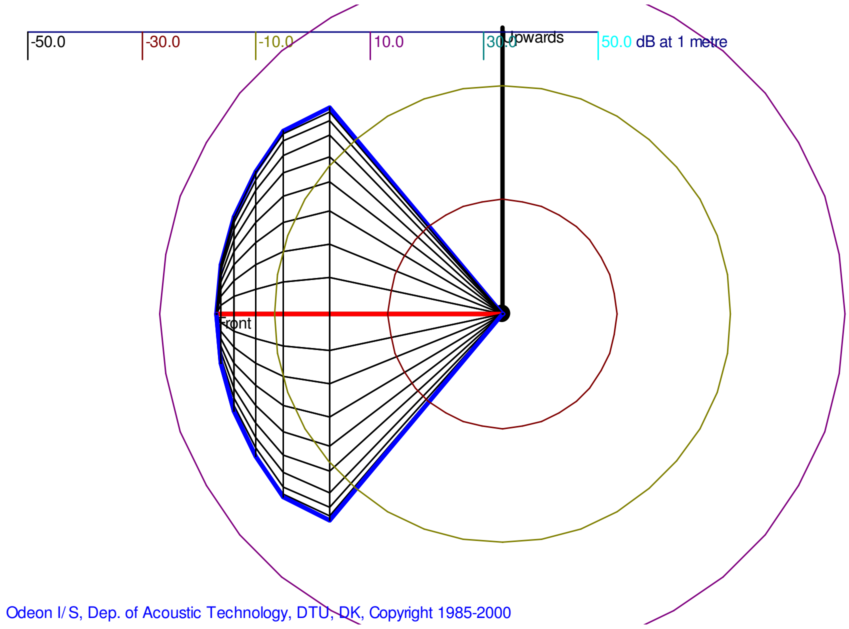
The early energy parameter E50 is defined as the integrated energy received during the period 0-50ms, time related to direct sound arrival and level related to the free field level at 10m distance from an omni directional source, which is identical to the reference level of the G parameter. E50 was calculated from the usual D50 and G parameters by the formula

$$E50 = 10 \cdot \log[D50 \cdot 10^{G/10}] \quad (1)$$

In order to investigate the behaviour of directional performance sources in reverberant field, a concert hall and a rehearsal room were computed in different room conditions. Each room condition was analysed as follows:

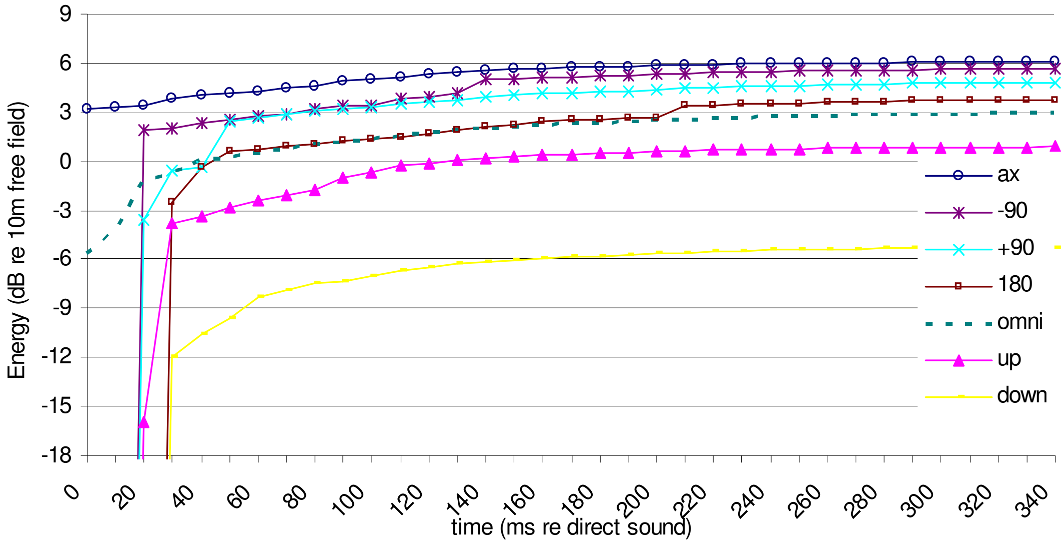
1. The sound transmission from source to receiver was separated into 6 separate room acoustic channels by the principle illustrated in *Figur 3*

2. The 6 room acoustical channels were separated by using a custom directivity pattern in ODEON that provided a beamwidth of ±45 degrees around each of the 6 channel axis. The level difference between inside and outside the beam (actually, it is a cone) was set to 100dB, which defines the channel separation at the input, *Figur 5*.

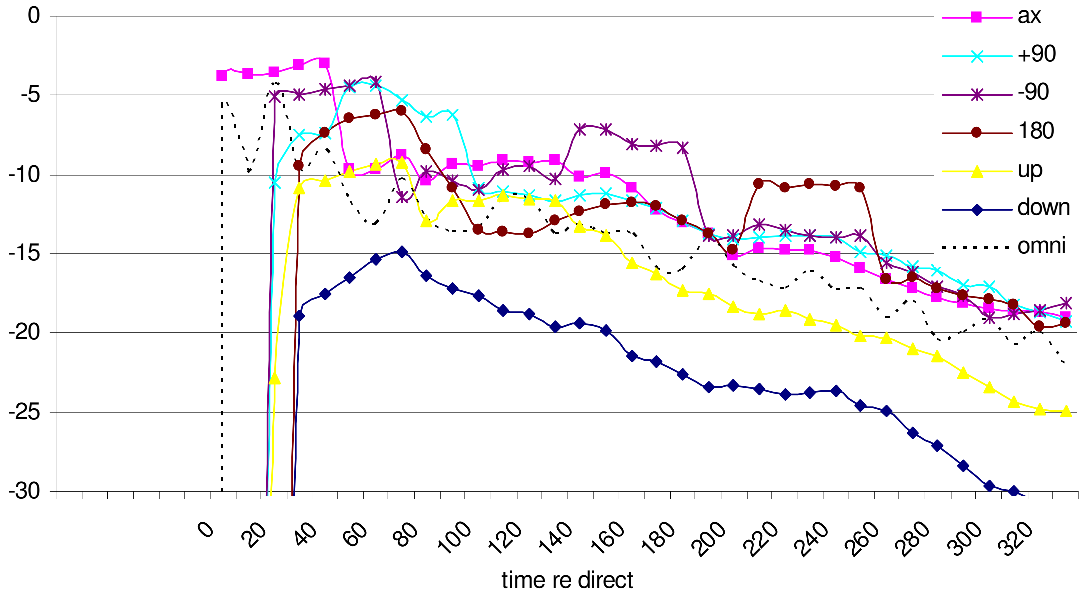


Figur 5: Polar diagram showing the directional pattern of the source customized in ODEON, providing a room acoustical channel input with 100dB separation.

3. E50 was computed by ODEON 7.0 for each of the 6 channels. The build up of cumulated energy and time-energy response in the channels of Elmia Hall is shown in *Figur 6* and *Figur 7* respectively.



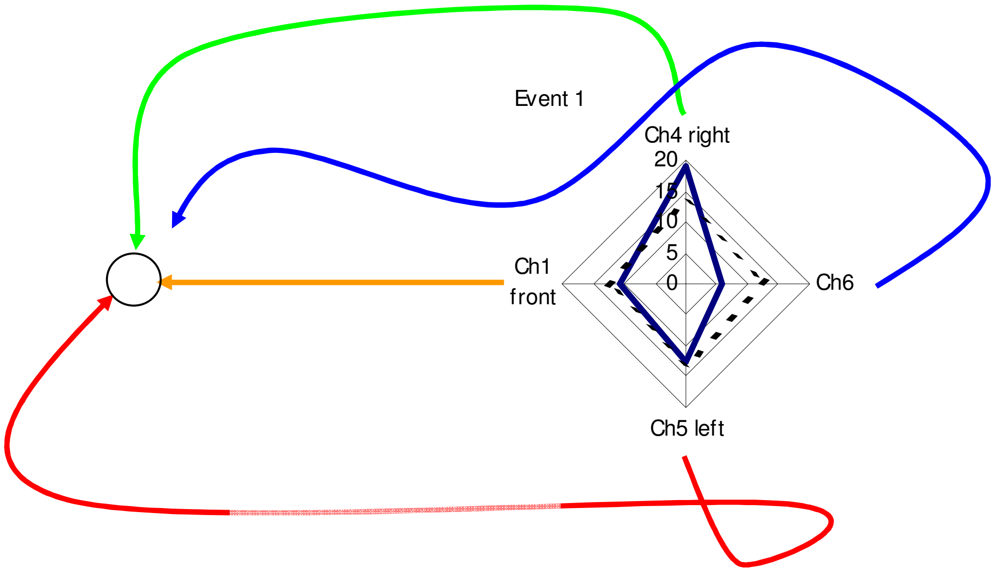
Figur 6: Cumulative energy build-up in the six room acoustic channels applied to Elmia Hall. The diagram indicates that level differences are established early <50-80ms and then maintained throughout the reverberation sequence. E50 for each channel is the value at 50ms.



Figur 7: Energy-time diagram for the six room acoustical channels applied in Elmia Hall with the source located in an orchestra on stage. A rectangular 50ms window filter has been applied in order to simulate time-merging of human hearing. The low level in the downward channel is due to absorption by the orchestra. The -90 and the 180 channels have potential echoes in 140-180ms and 220-260ms respectively.

4. A virtual source generating performance events with 6 separate directional channel outputs was simulated in separate software since ODEON 7.0 does not have a built in tool for this

5. In the same software, each source output was fed into its respective room acoustical channel, simulating the processing of the signal chain from source to receiver as illustrated in *Figur 8*



Figur 8: Summation of 4 of the total 6 room acoustical channels transmitting the 6 directional outputs from a source. The polar diagram illustrates the directional pattern of the source in the horizontal plane. The dotted curve in the polar plot indicates the level of an omni directional source of equivalent total energy.

6. For each virtual performance event the early energy (0-50ms) as a sum of the 6 channels was computed as show in the example below, *Tabell 1*

Example: The computational process for one channel for one source event could be as follows:

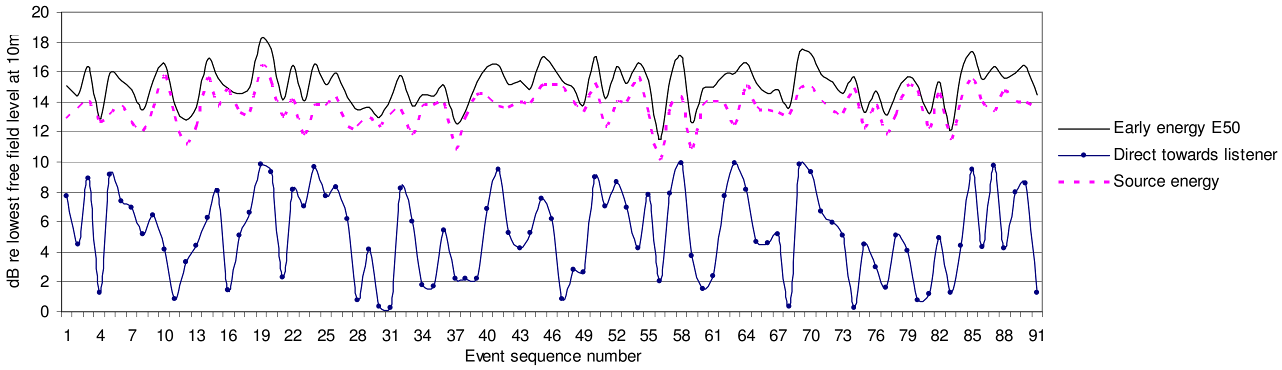
- E50 of room acoustical channel 1 is computed in ODEON to be 5dB
- Event 1 generates a channel 1 source output of 3dB (this is the input to room acoustical channel 1)
- Received early energy (0-50ms) via room acoustical channel 1 is 3dB + 5dB = 8dB
- Received early energy via all six channels are 8, -1, 13, 11, 10 and 18dB respectively, which by energy summation results in total received 21dB total received early energy
- The same procedure carried out for all frequencies of interest

Comment: In this case, channel 1 contains the source output of 3dB directed forward into the auditorium, so 3dB is the level of the free-field direct component at the receiver. Compared to this, the received early energy (<50ms) is 21dB, which is 18dB higher than the direct sound component. This illustrates the significant, random differences between direct sound and early energy.

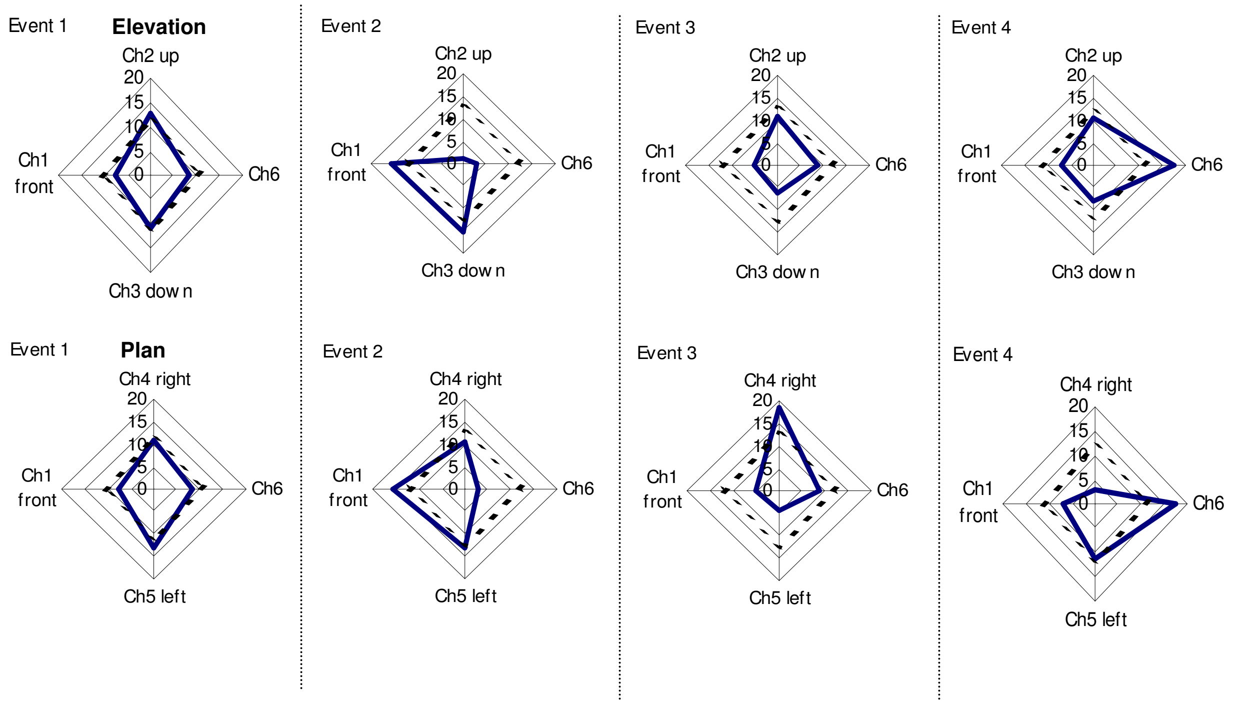
Tabell 1:Computation of early energy as a result of 6-channel transmission, for the first event in a temporal sequence.

Computation of Event 1	*Ch 1*	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	**Sum**
Source output = room acoustic input	***3***	1	15	10	8	17	**20**
Room acoustic transmission E50	*5*	-2	-2	1	2	1	**-**
Received early energy (<50ms) level	*8*	-1	13	11	10	18	**21**

7. The virtual source generated a sequence of 256 performance events, simulating the temporally changing source radiation within a preset range (e.g. 0-20dB) of source channel output, *Figur 9* and *Figur 10*. This was carried out for the source output ranges 10dB, 20dB, 40dB and 80dB. The 6-channel discretion inherently restricts the maximum source directivity to D=6 and directivity index to DI=7.8dB, by definition.



Figur 9: Simulated sequence of performance events within a 20dB dynamic and directivity range, received by listener in Elmia Hall (ODEON standard room), through 6 room-transmission channels. The curve illustrates how E50 correlates stronger with the source signal than does the direct component alone. For an omni directional source the direct sound would have correlated 100% with the source energy curve, which is clearly not the case for this arbitrary non-omni-directional source. The curves are plots of the values in the cells with bold numbers in the computation matrix Tabell 1.



Figur 10: Directional patterns of the source output in a sequence of four events in a simulated performance. Dotted curve indicates the source output of an omni-directional equivalent. The upper row shows radiation in the vertical plane, while the lower row shows radiation in the horizontal plane.

8. Finally, correlation between received early energy levels (0-50ms) and the source energy was computed for all room conditions, and for the four output ranges

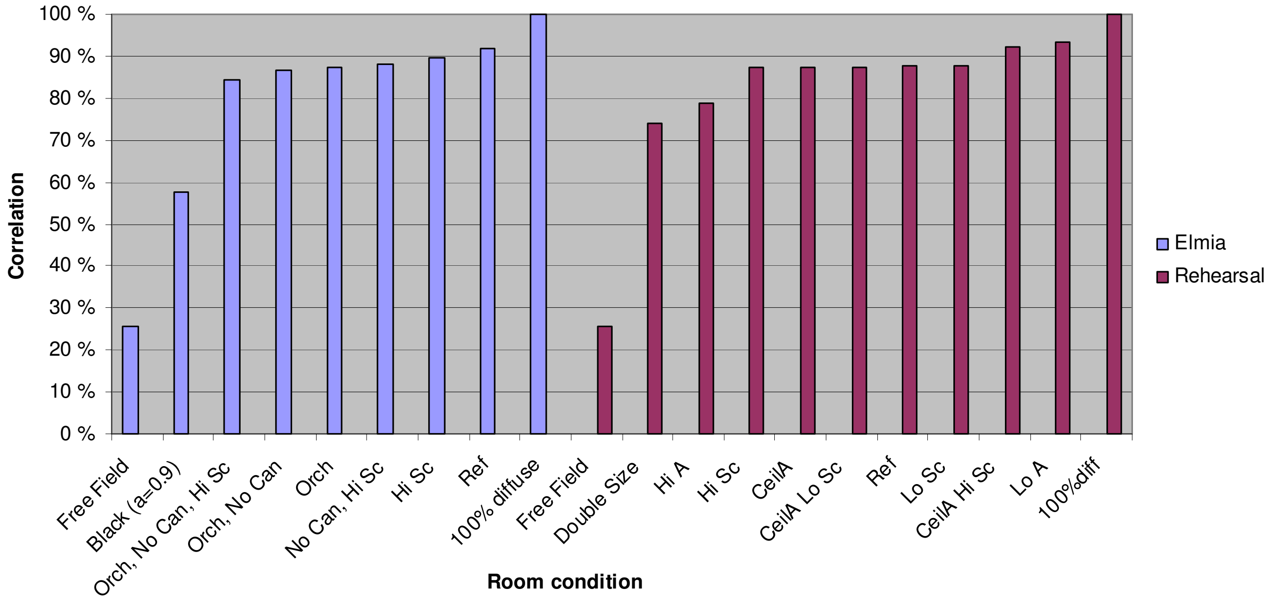
9. To obtain frequency spectra, the whole procedure must be carried out for each frequency band of interest. This was not part of this investigation.

7. EVALUATION OF COMPUTED RESULTS

The simulation process described in the previous section resulted in early energy level (integrated 0-50ms relative to direct sound arrival) sequences at the receiver in the Elmia hall and a parallelepiped rehearsal room simulated in different room conditions, and for four different ranges of source output. Correlation between received sequences and source sequences (sum of emitted energy over all directions) were measured and then evaluated by assigning the single number correlation value to a percentage scale. On this scale, 100% correlation will occur when the room acoustical channels have perfectly equal early energy (E50) transmission, while 0% would occur only for an infinitely directive source pointing the beam away from the listener in a perfectly an-echoic room. For sources of directional and dynamical variations within a range of 10dB, 20dB, 40dB and 80dB, the an-echoic condition would result in the average 26% correlation between received and emitted signal (in this context, signal is a sequence of performance sound events). Average of correlation with the four variation ranges is shown in *Figur 11*.

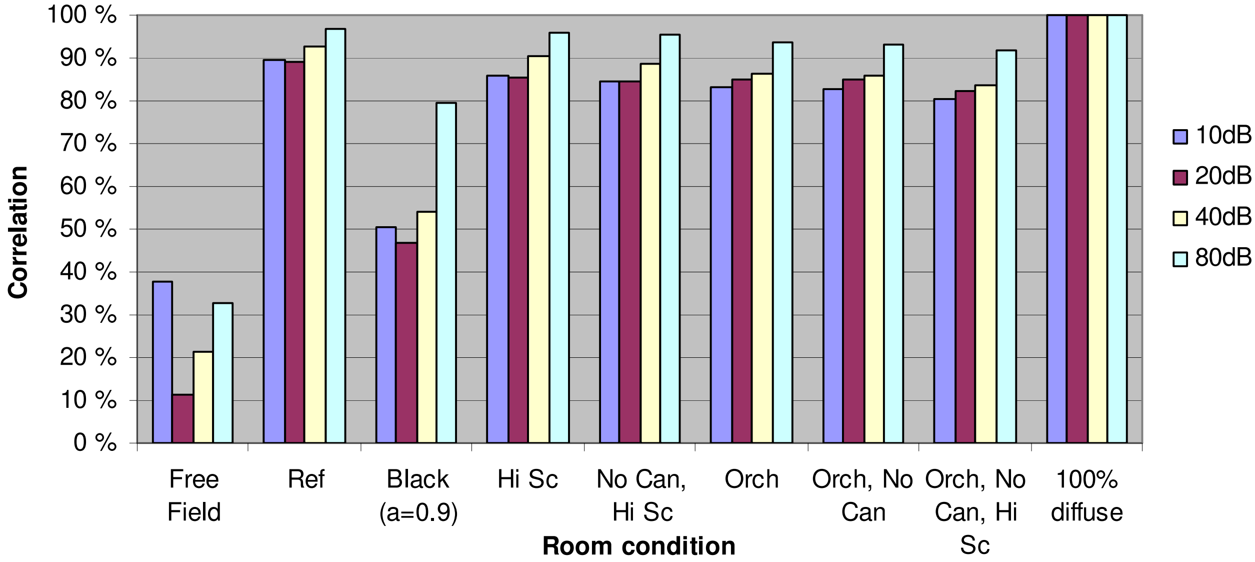
Room conditions have been chosen in order to study the influence from surface scattering, absorption in walls and floor, absorption in ceiling and size in the rehearsal room, while in the Elmia Hall the varying conditions are due to surface scattering, absorption and the presence of an orchestra and an overstage canopy.

Results are discussed in section 8.

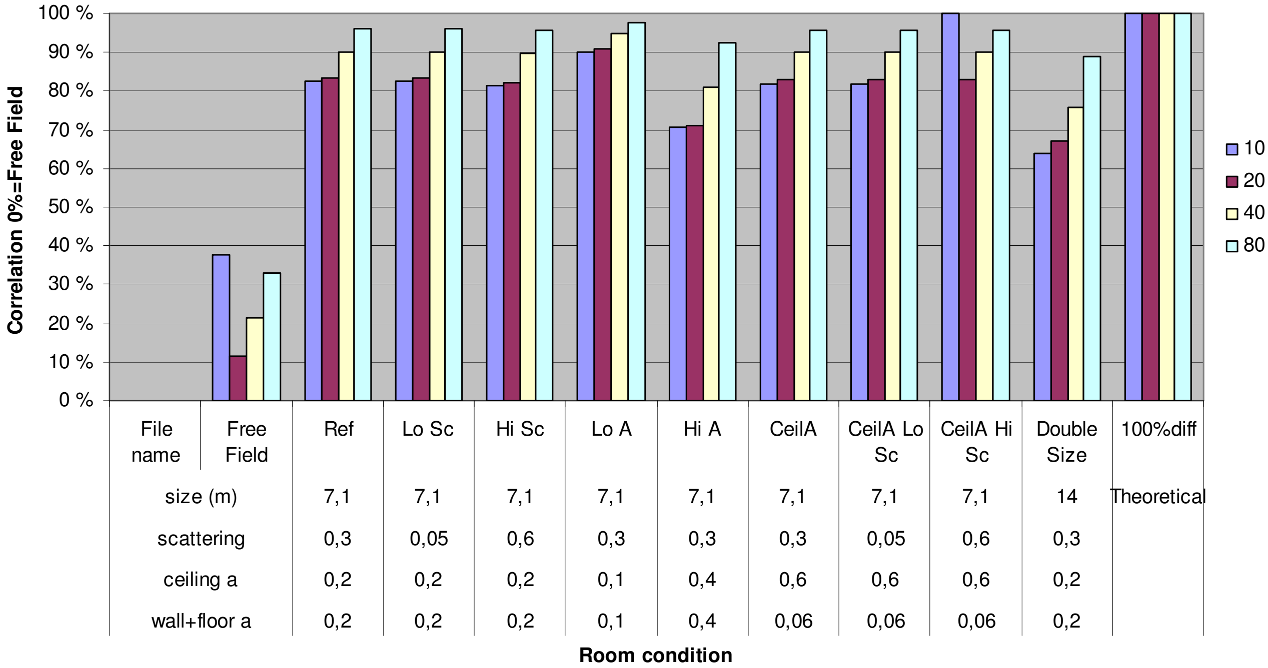


*Figur 11: Correlation between produced energy and received early energy (< 50ms) for different room conditions in Elmia Hall and a 3*4*5m3 rehearsal room (Double size: 6*8*10). Sc=scattering; A=absorption; CeilA=A concentrated to ceiling. Ref= Reference room condition, Elmia in standard ODEON condition, and rehearsal room with 20% absorption and 30% scattering on all surfaces.100% diffuse indicates the theoretical maximum.*

More detailed results from different output variation ranges are shown in *Figur 12* for Elmia and in *Figur 13* for the rehearsal room.



Figur 12: Correlation between produced energy and received early energy E50 (50ms) for different room conditions in Elmia Hall. Parallel series for 10, 20, 40 and 80dB range of source directivity and dynamics (max to min in dB). Can=Canopy, Sc=scattering, Orch=with orchestra. Black has 90% absorption on all surfaces.



Figur 13: Correlation between produced energy and received early energy E50 for different rehearsal room conditions. Parallel series for 10, 20, 40 and 80dB range of source directivity and dynamics (max to min in dB). Sc=scattering; A=absorption; CeilA=A concentrated to ceiling; Hi=High; Lo=Low.

8. DISCUSSION OF THE RESULTS

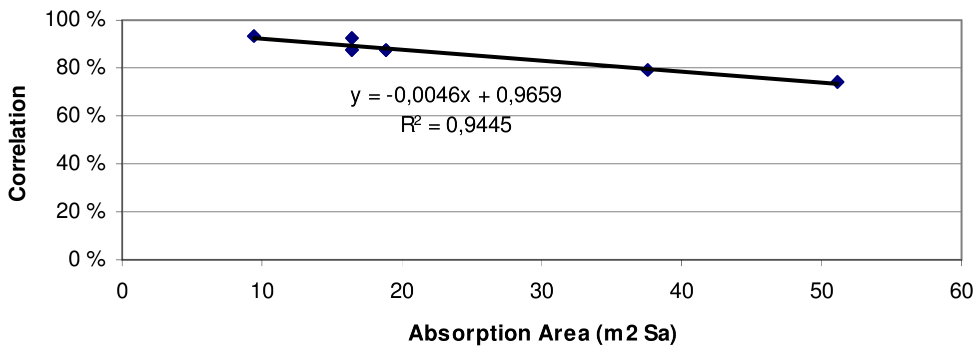
It is presumed that the room conditions with the higher early source-receiver correlation (ESRC) have the better early sound transmission quality.

For the purpose of this paper ESRC is defined as the correlation between energy radiated from the source (total over all directions) and received E50.

8.1. Rehearsal room

The rehearsal rooms in the reference condition had 20% absorption and 30% scattering evenly distributed on all surfaces. As can be seen from *Figur 11*, the rehearsal room with only 10% absorption showed the best result among the rehearsal rooms, closely followed by "CeilA Hi Sc" which has the absorption concentrated to the ceiling, while total absorption is approximately equal to the reference condition, and with surface scattering increased to 60%. Sound transmission quality does not seem to respond to changes in surface scattering alone in this rehearsal room. The most prominent negative effect appears to come from a doubling of all room dimensions, but also do we see a significantly negative effect from a doubling of absorption in the rehearsal room.

Investigating the covariance with volume an absorption area A (m^2 Sa), indicates that source-receiver correlation is very sensitive to A, with an explanation degree of 94% (Pearson's R-square = 0.9445) in the rehearsal room selection, see *Figur 14*. However, this does not seem to be a trend that extends from rehearsal rooms to the concert hall. Covariance with room diagonal is -75%, but the explanation degree is moderate as R square equals 56% on the diagonal parameter, probably since diagonal selection is small.



Figur 14: Covariance between source-receiver correlation and absorption area.

Surprisingly perhaps, surface scattering does not seem to make significant difference as far as these rehearsal rooms are investigated, with an explanation degree of only 2%. This can be explained by the fact that diffusive conditions will be provided by the restricted volume of these rooms, according to the effect discussed in section 5. However, the importance of suppressing acoustic glare and echoes from plane surfaces is supported by experience, and one should keep in mind that the energy models applied here does not take wave phenomena like comb-filtering and into account. See discussion of scattering, below.

8.2. Elmia Concert Hall

Our investigation of the different room acoustical conditions of Elmia (ODEON standard room) indicates that its basic configuration is the better one, showing 92% source-receiver correlation. Surprisingly again, surface scattering appears to have little impact on the ESRC. The factors that seems to reduce the source-receiver correlation is the introduction of the orchestra, and the removal of the canopy ("No Can"), *Figur 11*.

Like in the rehearsal room, a higher degree of surface absorption appears to be the very detrimental to ESRC with source-receiver correlation below 60%. For reference, the free-field condition has correlation 26%.

8.3. Multi-channel E50 as predictor

Elmia Reference	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Omni equivalent	Average deviation
E50	5	-2	-2	1	2	1	1,5	1,9

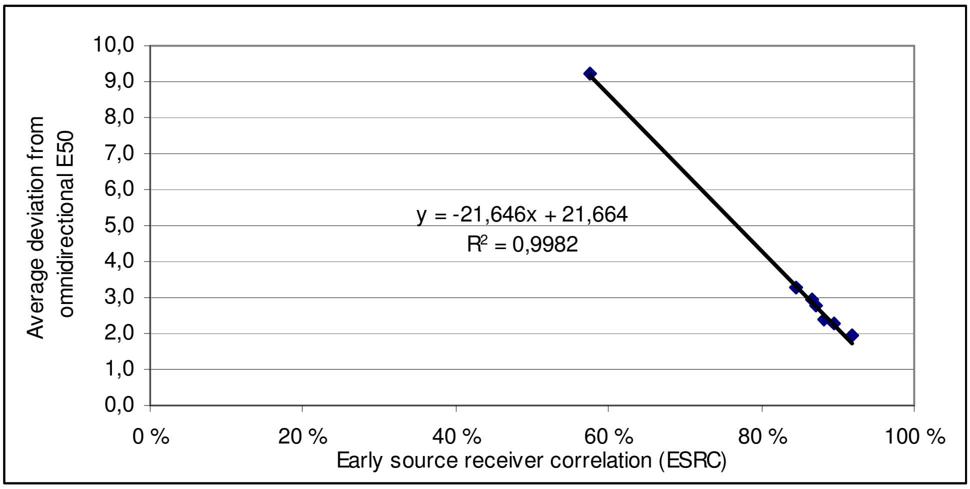
In search of potential parameters that could be used for predicting the ESRC, a very strong candidate were found in the average absolute deviation from the omni directional equivalent to the 6 channel set of predicted E50's. If the E50 of the i-th channel is denoted $E50_i$, and omni equivalent is denoted E50* then the average deviation is

$$OmniDev_{E50} = (|E50_1-E50^*|+|E50_2-E50^*|+\ldots\ldots+|E50_n-E50^*|)/n,$$

where E50* is the average energy level of the n E50's.

The average deviation co-varied more than 99% with the ESRC, with high explanation, $R^2>99\%$, in the seven Elmia hall condition tested. Though the selection is small, this is a quite promising trend. Therefore the E50 omni-deviation

$OmniDev_{E50}$ is suggested as ESRC predictor.



8.4. Surface Scattering

It is concluded that the degree of surface scattering does not affect the ESRC significantly in the selection of room conditions and the test setup used. One possible reason is that the directivity of the sources is less than D=6. Higher directivities and more narrow beam-widths may give a quite different picture, with significance to higher frequencies. This will be investigated in further research.

A more detailed comparison between energy-time diagrams of rooms with different degree of scattering has unveiled that added surface scattering seems to stretch the energy-time curve so that the cumulative early energy build-up is slowed down, as if the room was bigger than it actually is. This is perhaps to be expected, since scattering in general tends to send sound on detour, instead of following the shortest reflection paths inherent with specular reflections. It also supports the general opinion that scattering (diffusion) makes the room appear bigger.

Our study of rooms with different scattering properties does not take directions as seen from the receiver into account, since the main objective was total received early energy (before 50ms). It is evident that scattering suppresses spatial unevenness, and this should be possible to predict and measure when focus is on concerns like false localization, sound shadows, acoustic glare, comb-filtering / colouration and echoes.

9. FURTHER RESEARCH

After the investigations reported in this paper, there are some questions to be answered in further research:

- What is the average level deviation from the omni-equivalent source, of the free-field components in different directions? This should be investigated in order to describe statistical properties in both time and frequency.
- What is the characteristic dynamic output range of directional performance sources, as measured with multi-channel technique in an-echoic room during performance?
- What is the correlation between directional radiation components and the total radiation (the omni directional equivalent)?
- What is the correlation between directional radiation components and direct sound at the performer's ears?
- How does the average listener respond to variations in source-receiver correlation (ESRC)?
- What is the significance of all this when it comes to Support and Mutual Hearing (Ensemble)?
- Can we prove that surface scattering is increasingly significant to ESRC at higher directivities?
- Can we describe the room acoustical properties of a performance space in terms of an early sound transmission index ESTI that measures the degree to which a room compensates for unpredictable and unreliable source radiation behaviour? The $\mathrm{ESTI} = \mathrm{OmniDev}_{E50}$ is suggested as a possible candidate.
- How will a typical directivity / beamwidth spectrum (i.e. frequency distributed directivity) affect the ESRC?
- What is the unit length of a performance event in the context of this paper? 50ms is suggested, since shorter periods will merge together in human hearing
- The consequences as to stage acoustics will be investigated. This is very important, since the performer and ensemble colleagues are strongly exposed to direct sound. Taking source directivity into account may add to the understanding of support and ensemble hearing, and how it can be predicted, measured and evaluated.

We plan to analyze multi-channel recordings of musical instruments to try to find answers to these questions.

Diffusion and diffraction of sound from colleges in an orchestra is important, and could probably be considered as an integrated part of the directional properties of an instrument in an orchestra. This should be investigated further, since it is expected to be very important to audience as well as ensemble colleagues.

10. CONCLUSION

It is widely recognised that music and speech sources are not only directive and frequency dependant, the spatial and spectral radiation pattern changes rapidly and randomly with time.

Performance spaces of different acoustical condition have been analysed in 6 virtual channels with room acoustical simulation software. A source of random radiation varying with time and direction has been simulated and used as input in the simulated room acoustical channels. The free-field direct components from a time varying directional source correlates poorly with the total (omni-equivalent) energy produced. Rooms of adequate size can provide reliable early sound transmission that compensates for the shortcomings of the direct component. E50 is defined as received energy within 50ms after first arrival of sound, and the simulations shows that E50 correlates highly with sound energy produced by the source, and significantly better than the free-field condition.

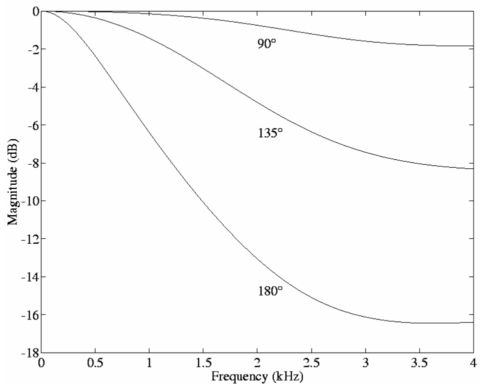
Excess sound absorption and room size proves to be the most prominent threats to the correlation between received early sound and produced sound. As long as rooms are small, sufficient early sound seems to be guaranteed irrespective of the distribution of surface absorption and scattering. This is significant to rehearsal rooms, but also when considering size in concert hall design. Dependence of size can be explained by image sources in image rooms, in an image space containing the real room.

The significance of surface scattering must be investigated with even more directive sources than applied in this study so far, in order to predict the effect of a sound beam hitting only a part of a wall, ceiling or floor.

Diffusivity and its temporal, spectral and spatial domain are discussed by theses and antitheses. The term diffusivity includes the room acoustic property that contributes to smooth out and compensate for negative effects of directive sources.

This far, the study of directivity confirms that the use of omni directional sources as representation for directional sources can be a dangerous pitfall, as it may result in that the answers one is searching for, remains hidden. An omni directional source can be adequate for statistical analysis of sound from general instruments with random directionality, but one should keep in mind that every listener is a point receiver, with no ear statistically distributed over the audience area.

Figur 15 shows an example of musical instrument directivity (from the paper template of BNAM 2006).



Figur 15: Directivity measurement of a trumpet.

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A visual presentation of this paper is available at www.akutek.info/Presentations/MS_Diffusivity_pres.pdf