PRESENTS

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by R. H. C. Wenmaekers, C. C. J. M. Hak and L. C. J. van Luxemburg

Abstract

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On Measurements of Stage Acoustic Parameters: Time Interval Limits and various Source–Receiver Distances

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Summary

The most widely recognized objective stage acoustic parameters are the Early Support (ST_{early}) and Late Support (ST_{late}). In these parameters the early and late reflected sound energy is measured within a certain time interval. Different time interval limits have been proposed for the stage acoustic parameters but there is no agreement on the preferable limits. There is a growing interest to measure stage acoustic parameters at various source to receiver distances. In this paper the influence of perceptual and architectural parameters, synchronicity, source to receiver relationship and the measurement system on stage acoustic parameters is discussed. Based on existing and new insights an optimization and extension of the ST parameters is proposed such that they can be measured at any distance between source and receiver using the most appropriate time interval limits. Theoretical assumptions were checked and confirmed based on systematic analyses of measured results for different concert hall stages with various conditions and various source to receiver distances.

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1. Introduction

Stage acoustics is concerned with the experience and appreciation of the acoustics by performers on stage in concert halls, opera houses, theatres and other venues for performing arts. Important acoustical factors for performers are the hearing of their own instrument, the hearing of others' instruments and the hearing of the acoustic response of the hall. The balance between these factors is important for playing ensemble [1, 2, 3, 4, 5]. Various objective parameters have been introduced to describe stage acoustics, all based on acoustic properties that can be found in room impulse responses. On stage, the room impulse response (RIR) contains the direct sound and sound reflected from the stage surroundings and the hall. Most objective parameters measure the amount of sound energy within a certain time interval by integrating over the squared sound pressure of a RIR. The choice of the time limits of the time interval may be based on a perceptual or architectural relevance, but might be influenced or limited by the used measurement methods.

Researchers have proposed different time limits; it is clear that there is no agreement on these time interval limits. So far, no studies have investigated the effect of the choice of time limits on measured stage parameters. In this paper, the available parameters and their metrological issues are discussed in section 2. In section 3, the perceptual, architectural and orchestral principles of time delays on stage are explored. In section 4 it will be discussed which time intervals and measurement conditions seem most appropriate resulting in a proposal for optimisation and extension of currently used stage acoustic parameters. In section 5, theoretical assumptions are checked using a large set of measurement data of different concert halls. The stage acoustics of the measured halls is evaluated through the optimised and extended stage acoustic parameters in section 6. Finally, the results are discussed in 7 and the main conclusions are presented in section 8.

2. Stage acoustic parameters

The most widely recognized objective stage acoustic measures are those as proposed by Gade. These measures are based on laboratory and field experiments as described in [3, 4]. Experiences with these parameters have been discussed by Gade in [6, 7]. Two parameters have been included in the annex of the standard ISO 3382-1 [8] on the 'Measurement of room acoustic parameters – Performance spaces' since 1997: Early Support (ST_{early}) and Late Support (ST_{late}). Other parameters like ST2 or ST_{total}, Clarity Stage (CS) and Early Ensemble Level (EEL) have not

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been included in the standard. In the following paragraphs the development of the various parameters will be treated. This development clearly illustrates the issues and discussions related to time intervals on stages.

2.1. Early Support

The ST_{early} was intended as a measure to describe the assistance of early reflections to the hearing of the own instrument. At 1 m distance, it measures the difference between the reflected sound level within the 20–100 ms time interval after the arrival of the direct sound and the sound level of the direct sound plus floor reflection, measured in the time interval 0–10 ms of the RIR [8].

Originally, the lower time limit of the time interval 20 to 100 ms was 10 ms instead of 20 ms [2]. However, the lower limit was changed to 20 ms because it was difficult to isolate the direct sound within 10 ms in the low octave bands with the available measurement techniques using octave band filtered sweeps [9]. As a consequence, in the current ST_{early} parameter a gap exists between 10 and 20 ms where sound energy is not taken into account. Therefore, in practice, it is recommended to place the transducers at a minimum distance of 4 m from any stage boundary of interest to avoid sound arriving within the 10 to 20 ms time interval [6, 10].

Two different upper time limits 100 ms and 200 ms were used in two different parameters ST1 and ST2 respectively. The name ST1 was replaced by ST_{early} in 1992 to avoid confusion with another parameter Speech Transmission Index STI [6]. ST2 was replaced by ST_{total} with a numerator time interval of 20 to 1000 ms (ST2 is sometimes mistaken by researchers for ST_{late} [11]). ST2 was intended to describe the amount of support from the room. However, it was not included in the ISO standard. According to [7], it has never been investigated whether the 100 ms upper time limit for ST_{early} is the optimum choice.

2.2. Late Support

The parameter Late Support (ST_{late}) was intended as a measure to describe the perception of reverberance. At 1 m distance, it measures the difference between the reflected sound level in the time interval 100–1000 ms after the arrival of direct sound and the sound level of the direct sound plus floor reflection, measured in the time interval 0–10 ms of the RIR [8].

Originally, the clarity C_{80} parameter was used at 1 m distance to measure late support, also known as Clarity Stage (CS), measuring the ratio of sound energy arriving within the time interval 0–80 ms and after 80 ms to infinity [8]. In the CS it is assumed that the amount of energy before 80 ms at 1 m distance is dominated by the direct sound [4]. The energy after 10 ms was omitted in the numerator, the upper boundary increased from 80 to 100 ms and numerator and denominator switched to match the ST_{early} definition resulting in currently used ST_{late}.

At first, time to infinity was chosen as an upper time limit instead of 1000 ms [3, 4, 5]. However, in 1992 the upper time limit was fixed to 1000 ms, comparable to the C_{80} parameter definition that was used in [5], although Reichardt *et al.* [12] originally proposed infinity. At that time, the 1000 ms upper limit was chosen in order to save calculation time. According to [9], the influence is negligible in typical acoustic conditions of a concert hall.

The ratio between ST_{early} and ST_{late} seems to be useful for describing the degree of masking of ensemble information by late reflections [6].

2.3. Early Ensemble Level

The parameter Early Ensemble Level (EEL) was intended as a measure to describe the ease of hearing others [3]. It measures the difference between the direct and reflected sound level within the time interval 0–80 ms after the emission of the sound and the sound level of the direct sound plus floor reflection, measured in the time interval 0–10 ms of the RIR at 1 m distance. An interesting feature of this parameter is its sensitivity to the effect of the time delay that occurs between musicians sitting at a distance from each other. The temporal window for measured arriving direct and reflected sound narrows when the source and receiver are further apart. As a result, EEL can only be measured at a distance between 2 and 27 m.

It is striking that an upper time limit of 80 ms was used in the EEL instead of the 100 ms in the ST parameters. However, this may have been different for the sake of comparison with the clarity C_{80} [9]. To the knowledge of the authors, it has never been investigated whether the 80 ms upper integration limit is the optimum choice for the EEL.

After comparison of the parameters with measured subjective parameters by questionnaires ST_{early} appeared to correlate better with the 'hearing of others' or the 'ease of ensemble' than EEL, which was originally intended for this use [4]. This paradox is not yet fully explained [7]. Nevertheless, ST_{early} is recommended to be used in relation to 'ensemble i.e. ease of hearing other members of an orchestra' and EEL was not used in further analyses or added to the standard [3, 4, 8].

2.4. Measurement conditions

The RIR for deriving the ST parameters should be obtained at 1 m distance between an omnidirectional sound source and receiver, chosen as a distance to be comparable to the distance from the performer's ear to his own instrument. The sound source distance is measured from the physical centre of the sound source, described in the ISO standard as the 'acoustic centre'. Both the sound source and the microphone height from the floor should be either 1.0 m or 1.5 m [8]. However, in an earlier version of the standard from 2006 the transducers' height could vary between 1.0 and 1.5 m. No suggestions are made for the choice of transducer height. Nevertheless, Gade recommends using a 1.0 meter transducer height because it represents the acoustic centre of most musical instruments best and because it may give a more realistic effect of eventual attenuation of furniture and seats [9].

It is recommended to perform at least 3 measurements at different positions on stage and the positions should be reported [8]. No comments are made on the orientation of the microphone relative to the sound source. In the concept of the ST parameters, the sound source represents the instrument and the microphone represents the musicians' ears. In most cases the instrument is in front of the musicians who are facing the conductor. This suggests that the sound source and microphone should be put in a line crossing the conductors' position, where the source is in between the conductors' position and the microphone. In most research in which ST parameters were measured, the source and receiver are represented as a single location on stage without reporting source to receiver orientation [3, 10].

As mentioned earlier, all transducers should at least be kept 4 meters away from any stage boundaries. Also, when the orchestra is not present during measurements, as is often the case, chairs and music stands must be present. However, chairs and stands should be removed in a radius of 2 m around the transducers to avoid reflections arriving within the time interval 0 to 10 ms [6, 8]. It is striking that between 2 and 4 m distance around the transducers seats and stands are allowed, possibly causing reflections in the 10–20 ms time interval.

2.5. The reference sound level

In the concept of the ST parameters and EEL, the direct sound of the sound source at 1 m distance is used as a reference, sometimes denoted E_e(dir) where 'e' stands for emission (which is especially important for EEL). In current practice, the direct sound and floor reflection are measured within the time interval 0–10 ms [8]. In case of transducers heights of 1.0 m the floor reflection will arrive 3.6 ms after the direct sound. For the 250 Hz octave band, which is most critical, these two components will be smeared out over the whole time interval 0–10 ms [6]. When the transducers are set at a height of 1.5 m the floor reflection will arrive 6.3 ms after the direct sound.

2.6. Variations on the support parameters

Some research presented at conferences has discussed the measurement method for the direct sound reference E_e(dir). It was suggested that the floor reflection should be absorbed by sound absorbing material [13], but an average difference was found less than 0.5 dB. Also it was suggested to use a floor-reflection-free time interval of 0–5 ms [14]. One other issue is how to deal with the directional characteristics of the standard omnidirectional sound source at high frequencies. It should be noted that researchers have used different types of omnidirectional sound sources. For instance, in the 80's Gade used an icosahedron sound source with a 500 mm diameter containing 20 loudspeakers, while nowadays the dodecahedron sound source is commonly used with a smaller diameter of approximately 350 mm containing only 12 loudspeakers. This may result in less smooth directivity patterns especially at high frequencies. If the sound source is not adequately omnidirectional, Gade [6] suggested that the source should be rotated such that always the same directivity maximum is pointing towards the microphone. For this position, the deviation from the sound level at 1 m distance derived from a sound power measurement in the laboratory should be determined and used as a correction. A comparable option was suggested by Dammerud *et al.* [15], who suggested to use the sound power calibration methods as described in [8]. However, these methods exclude the influence of the floor reflection. Hak *et al.* [16] showed that for a single measurement at 1 m distance and a 1.5 m transducer height a maximum absolute error of 1.5 dB, 3.5 dB and 3.5 dB can be made in measured sound level for octave bands 1, 2 and 4 kHz respectively using a common standard omnidirectional sound source on stage. Maximum possible level deviations are reduced to below 0.5 dB for all frequency bands when averaging over 5, 7 or 8 measurements of equal angular stepwise rotation. Furthermore, it was shown that the difference between the average value derived from three different precision G calibration methods and a (in situ) on stage sound power measurement at 1 m distance is −0.8, 0.0 and +0.7 dB for the low, mid and high frequency range respectively when using 8 impulse responses while rotating the sound source in 45 degree steps [17]. These differences are similar to the accuracy of the three precision methods themselves. This suggests that the E_e(dir) component can be measured on stage with 0.5 dB accuracy, when using an average of 5, 7 or 8 measurements of equal angular stepwise rotation, without removing the floor reflection or performing off-site calibrations. The influence of directivity deviation is only investigated for the total sound level but has not yet been investigated for room acoustical parameters.

Another series of papers have discussed possible variations in time intervals for the ST parameters. It was suggested by Chiang *et al.* to extend the ST_{early} time interval from 20–100 ms to 7–100 ms [18] or 5–80 ms [19]. This way, ST_{early} could be used to perform measurements closer to the stage boundaries. These parameters were denoted ED100 and ED80 respectively. Comparable to the ED80, the LD80 was suggested extending the ST_{late} time interval from 100–1000 ms to 80 ms to infinity. In a similar way, the Late Sound Strength G_l was suggested by Dammerud [15], where the time interval 80 ms to infinity is measured at 1 m distance relative to the reference sound level at 10 m in the free field. When using 1000 ms as a upper time limit, the impulse response should not contain noise within the 0–1000 ms interval, but this is not easily controlled. Using time to infinity instead of 1000 ms as an upper time limit is perceptually clearer. However, in both cases the noise tail of the impulse response can be of influence on the result. The relationship between the impulse response and the noise tail (the decay range) can be described by the Impulse to Noise Ratio (INR) [20]. An INR of at least 45 dB for a measured RIR on stage is recommended by the authors, where time to infinity is defined as the time of the cross point between the decay curve and the noise floor of the impulse response [21].

Also, parameters similar to the EEL have been proposed in some conference papers. Braak and Van Luxemburg

[22] proposed a parameter, denoted LQ_{7-40}, that is measured where source and receiver positions represent different musicians on stage. The parameter measures the difference between the early reflected sound level in the time interval 7–40 ms and the late reflected sound level in the time interval 40 to infinity. It is different from the EEL concept because the direct sound is omitted from the time interval. Also, the time interval is not dependant on the source to receiver distance like the EEL. The masking of ensemble information by late reflections is measured, comparable to the ratio between ST_{early} and ST_{late}. No reference is made to the sound level at 1 m distance.

Vercammen and Lautenbach [23] and Dammerud *et al.* [15] used a similar approach omitting the direct sound from the measure using an interval 5–80 ms and 7–50 ms respectively. Both use a reference sound level at 10 m in the free field using the G and therefore are denoted G_{5-80} and G_{7-50}. Ueno and Tachibana [24] also note in their paper that, in case of measuring EEL, the direct sound should be omitted in order to evaluate the early reflections. Finally, Dammerud *et al.* [15] also proposed the Early Sound Strength G_e were a time interval of 0–80 ms is used without omitting the direct sound. It is stated that the G_e and G_{7-50} measured with source receiver distances larger than 1 m are highly influenced by the presence of the orchestra [25].

2.7. Other stage acoustic parameters

Other parameters have been used that are not based on energy ratio's like the Early Decay Time (EDT) which was originally introduced for describing auditorium acoustics [26] and the Modulation Transfer Function (MTF) as used in the Speech Transmission Index (STI) [27]. However, these parameters do not directly rely on time intervals and are therefore not further reviewed in this paper.

3. Relevant time intervals on stage

In general, there are three different aspects that seem important to objectively describe the acoustic conditions on stage: the direct sound, the early reflections and the late reflections. In the previous section it was shown that variations have been made in the stage parameters by different researchers. It is clear that there is no agreement on the time interval limits in the stage acoustic parameter formulas. In this section, the influence of five different aspects on the choice of time interval will be investigated.

3.1. Perceptual parameters

The main goal for defining an objective stage acoustic parameter is that it will correlate with the subjective experience by the musicians. Various studies have been performed where musicians were tested under controlled conditions in a laboratory, aiming to find the important aspects of the room impulse response that relate to ensemble playing. The results of these studies have been summarized by Gade [7]. Researchers have focused on the temporal characteristics like the usefulness or annoyance of delayed reflections, the frequency properties like bandwidth and frequency balance (timbre) and the level properties like audibility and masking. The studies have been performed with single players or small ensembles playing together. Although it may not be suitable to directly apply or extrapolate the results from these studies to a full orchestra situation, it gives information on what is important on stage. Marshall *et al.* [28] suggested as a first design guide that preferred early reflection delays should lay between 17 and 35 ms relative to the arrival of direct sound, based on experiments with delayed reflections at 10, 20, 40 and 80 ms where a trio was asked to judge their ease of playing ensemble. Gade [3, 4] also concluded that early reflections are an important factor for ensemble playing, based on experiments with musicians in different sound fields with a mix of three reflections at 23, 43 and 83 ms relative to the time of emission. He found that when the direct sound from the other is masked (by reverberation or the sound of other players), it cannot be fully compensated by strong but further delayed early reflections. Also, it was concluded that meaningful reflections for ensemble playing can arrive up to 100 ms and reflections up to 200 ms after the direct sound can provide support for soloists as long as they have the correct (moderate) sound level. Another interesting factor is that strong early reflections may also come too early between 5 and 20 ms and cause unfavourable coloration effects [29].

3.2. Architectural parameters

A second goal when defining an objective stage acoustic parameter is the applicability as a tool in optimizing stage environments through experiments with measurements or designing stages through simulations. To be able to do so, the parameter should be sensitive to changes in architectural parameters like stage dimensions, hall dimensions and surface properties. To investigate the relation of stage dimensions to the stage acoustic parameters time intervals, an inventory is made of maximum delayed first order reflections from stage surroundings. A list of stage dimensions is used from Dammerud [30]. In his study the average stage-dimensions of 22 purpose built concert halls are summarized. Table I shows the minimum, average and maximum dimensions of these 22 stages. The ceiling height has either been determined from the physical ceiling or from a canopy or overhead reflector above the stage.

Table I. Minimum, average and maximum stage dimensions of 22 purpose built concert halls.

	min	average	max
Width [m]	15.5	22.0	35.0
Depth [m]	8.0	11.0	14.5
Height [m]	7.5	13.0	22.0

To find the possible maximum delay in reflections based on the dimensions in Table I three different rectangular geometric scenarios have been studied:

1. minimum stage size w×d = 15.5×8 m^2 + orchestra size w × d = 13.5×6 m^2;
2. average stage size w×d = 22×11 m^2 + orchestra size w × d = 20×9 m^2;
3. maximum stage size w×d = 35×14.5 m^2 + orchestra size w × d = 20×9 m^2.

With the 'maximum stage size', it is assumed that the orchestra is not using the whole stage.

Furthermore five different source–receiver (S-R) positions are used to find the maximum possible delays

1. front of stage on the side with S-R distance 1 m;
2. front of stage in the middle with S-R distance 1 m;
3. front of stage on the side to front of stage on the opposite side with S-R distance equal to orchestra width;
4. front of stage in the middle to front of stage on the side with S-R distance equal to half the orchestra width;
5. front of stage on the side to back of stage on the opposite side with S-R distance equal to (orchestra width^2 × orchestra depth^2)$^{1/2}$.

The three scenarios and its source and receiver positions are illustrated in Figure 1 with some examples of ceiling and back wall reflection paths.

The maximum delay in ms relative to the emission of the sound has been determined for every possible direct sound path or 1st order reflected via sidewall, back wall or ceiling for every combination of stage size and source–receiver, see Table II. It is shown that for an average stage size, the maximum delay of a first order reflection is 120 ms at 1 m S-R distance and 95 ms at larger S-R distances (O'Keefe [14] concluded that the boundary between the early discrete reflection zone and the late diffuse reflection zone ranges from just over 100 ms to just under 400 ms for 12 stages).

In all cases, the largest possible delay for a 1st order reflection is found for the shortest S-R distance and the maximum delay does not increase when the direct delay increases. This implies that in general the time interval between the arrival of the direct sound and the maximum 1st order reflection narrows when the S-R distance increases. For the average stage, the temporal window of possibly arriving 1st order reflections after the direct sound arrival is 31 ms at the largest S-R distance of 22 m diagonally crossing the stage.

3.3. Synchronicity

For the average stage, the delay in direct sound between different instruments rises up to 64 ms while the 1st order reflected sound arrives up to 120 ms, see Table II. The effect of these delays have already been described as early as 1826 by Chladni [31]:

> *'Der Raum, welchen ein Orchester einnimmt, darf [auch] nicht grösser seyn, als nöthig ist, weil sonst der (bey eines mässigen Temperatur der Luft etwa 1040 bis 1060 Fuss in einer Sekunde durchlaufende) Schall nicht schnell genug von einem Ende des Orchesters zum andern gelangen, und jeder Mitspieler die entferntern zu spät hören würde, so da als kein genaues Uebereintreffen im Takte Statt finden könnte, selbst, wenn man den Takt noch so laut schlagen, oder ihn wohl gar, wie bey den Alten üblich war, mit hölzernen oder eisernen Taktschuhen stampfen wollte.'*

Experiments by Gade [3] confirmed that with direct sound delays larger than 20 ms, corresponding to a 7 m mutual distance, the ease of ensemble decreased based on studies with six different sound fields. Besides acoustical delays, the musicians in the orchestra itself can intentionally play ahead or delayed. It is often stated that brass and percus-

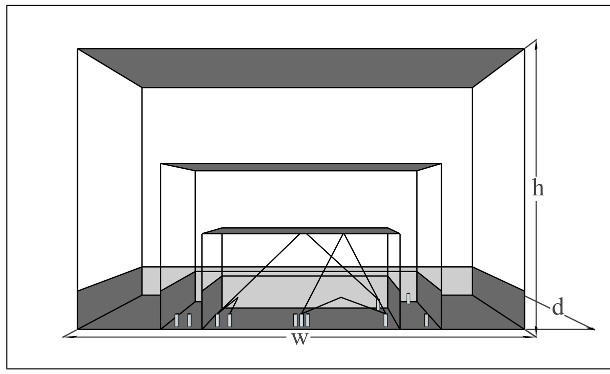

Figure 1. Three stage scenarios with minimum, average and maximum stage size. The source and receiver positions are represented by white columns of 1 m height.

Table II. Delay in ms relative to the emission of the sound for every possible sound path directly or 1st order reflected via sidewall, back wall or ceiling for every combination of stage size and source–receiver.

	S/R distance 1 m					
S/R pos	1. front side			2. front middle		
Stage size	min	avg	max	min	avg	max
Direct	3	3	3	3	3	3
Sidewall	82	120	157	45	64	102
Backwall	41	58	79	41	58	79
Ceiling	38	70	122	38	70	122
All max	82	120	157	45	70	122
	S/R distance > 1 m					
S/R pos	3. front side to side			4. front mid to side		
Stage size	min	avg	max	min	avg	max
Direct	39	58	58	20	29	29
Sidewall	45	64	102	65	93	131
Backwall	57	83	98	45	65	84
Ceiling	55	91	136	43	76	126
All max	57	91	136	65	93	131
	S/R distance > 1 m			maximum of		
S/R pos	5. front side to back side			all five cases		
Stage size	min	avg	max	min	avg	max
Direct	43	64	64	43	64	64
Sidewall	48	70	105	82	120	157
Backwall	46	66	78	57	83	98
Ceiling	57	95	138	57	95	138
All max	57	95	138	82	120	157

sion players sitting at the back of the stage play ahead of the conductors' baton [3]. This way, they aim to let the direct sound of the different instruments sections arrive simultaneously at the stage front line and consequently the listeners' positions behind the conductor in the hall. On the average sized stage, this effect could impose an extra delay up to 26 ms for the direct sound from the front row players being audible in the back of the stage after their own instruments' sound. Therefore, it may be relevant for reflections to arrive more early for sound travelling from the front to the back of the stage.

3.4. Source to receiver relationship

Traditionally, when describing room acoustic parameters in a concert hall the whole orchestra is represented by a single omnidirectional sound source which is placed on stage at a minimum of 3 consecutive positions [8]. The listener is represented by a single omnidirectional microphone which is placed in the audience area at a minimum of 6 to 10 consecutive positions. This implies that usually less source positions than receiver positions are used and the receiver positions may be assessed per source position (see Figure 2a).

In stage acoustic measurements the number of source and receiver positions can be equal, because one can use the same location as a source as well as a receiver position. The distance between the source and receiver can represent the distance between the own instrument and the musicians' ear, like the 1 m distance in the ST_{early} and ST_{late} parameters or the mutual distance between two different players like in the EEL parameter. In the latter case, one could asses the transfer of sound from all different sound source positions towards a single receiver, as illustrated in Figure 2b.

The support by reflections is important for every combination of two musicians at various distances. Especially at larger S-R distances musicians may only rely on reflected sound for mutual hearing. Therefore, the transfer of sound on stage should be considered at various source–receiver distances.

One might be tempted to use more receiver positions than source positions because one can easily use multiple microphones to record the impulse responses simultaneously, while the sound source needs to be operated one at a time. Nevertheless, on stage, the transfer of sound from every position to the other seems equally important and using equal source and receiver positions on stage seems obvious. Although, in theory, the transfer of sound between both omnidirectional source and receiver is reciprocal.

Another aspect of the source to receiver relationship is the delay of the arrival of the direct sound after emission of the sound from the source. When for instance judging the clarity of the 'orchestra' at receiver positions in the audience area, the objective parameter C_{80} is used where the time interval of 0 to 80 ms and 80 ms to infinity is relative to the time of arrival of the direct sound. The C_{80} is determined for every source at a single receiver position without taking into account the delay of the direct sound

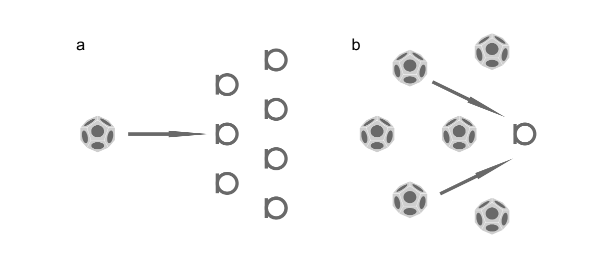

Figure 2. (a) single source towards multiple receivers, (b) multiple sources towards single receiver.

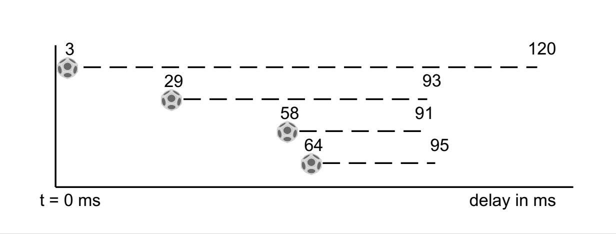

Figure 3. Arrival of direct sound (marked by source symbols and number) and time interval of possible arriving 1st order reflections up to its maximum (dashed lines and number) from self and 3 others, relative to the time of emissions at S-R distance of 1 m on position 'front side' on an average sized stage for synchronized sources.

arrival between the different source positions. This may be correct because the orchestra itself corrects for this delay in order that the direct sound arrives simultaneously in the audience area behind the conductor (see section 3.3). However, when the receiver is positioned in the orchestra itself, it might be necessary to compensate for the delay in arrival in the direct sound when studying the sound energy within a certain temporal window.

The architectural parameter analysis showed that maximum arrival times of early reflections from stage surroundings are approximately 91 to 120 ms relative to the time of emission for an average stage size. The above mentioned source to receiver model based on synchronized sources is illustrated in Figure 3. It clearly shows that for larger S-R distances the direct sound is delayed whilst the time interval of possible arriving 1st order reflection after that direct sound narrows.

3.5. Measurement system influence

In the stage parameter definitions the energy from the direct sound + floor reflection and the following reflections needs to be separated. Also it has been proposed to make the separation between the direct sound and the floor reflection, see section 2.6. However, here the limits of the measurement systems are reached and the physical disadvantage of low frequencies must be taken into account. Important factors are the signal response of the used sound source and the filter characteristics, which cause a smearing of the measured signal. This means that energy from adjacent reflections may overlap and the sound energy of each reflection cannot be isolated without the influence of these adjacent reflections. To avoid this, a certain period of time must be kept between the last and following reflection around the time interval limit. The minimum required distance between equally strong reflections was determined for a B&K 4292 omni directional sound source and Dirac room acoustic measurement software, where the RIR is first divided in the time domain and then filtered through band-pass filters as recommended by ISO 3382-1 [8]. It was found that a minimum distance between neighbouring reflections of 17, 12 and 9 ms is required to reduce the influence to ≤ 0.1, ≤ 0.5 and ≤ 1.0 dB respectively (for the separate octave bands 250, 500, 1000 and 2000 Hz). This suggests, that the reference level of direct sound + floor reflection at 1 m S-R distance (delay 4 ms at 1 m height) in the 250–2000 Hz octave bands should be measured without reflections coming earlier than 4+17 = 21 ms after the direct sound for ≤ 0.1 dB influence. Also, it seems to be impossible to separate the direct sound and floor reflection accurately using a single measurement. The sound level of a single reflection at $4 + 9 = 13$ ms can be measured at influence ≤ 1 dB, and when multiple reflections are measured in a wider temporal window the influence will likely decrease. At larger S-R distances the direct sound and floor reflection will merge and the sound level of a single reflection at 9 ms can be measured at an influence ≤ 1 dB.

When measuring sound levels, it is also necessary to take into account the size of the wavelength. When measuring the sound level of a single reflection, EN 1793 [32] recommends to use a time window of at least one corresponding wavelength. For the 250 Hz octave band with lower edge frequency at 176 Hz this suggests that the time window should at least be 6 ms. However, to effectively capture reflections on stage the time window should be much more than 6 ms.

4. Summary and proposal for extended ST parameters and measurement conditions

Perceptual studies by several researchers have shown that early reflections arriving before approx. 100 ms after emission of the sound are likely to be relevant for playing ensemble on concert hall stages for various source–receiver distances. Reflections arriving after approx. 100 ms can be described as late reflections which are necessary to provide a certain amount of reverberance. A new architectural analysis of common stage dimensions reveals that with an average stage size most 1st order reflections will arrive within 100 ms after emission of the sound. Also, it shows that in general the time interval between the arrival of the direct sound and the maximum delayed 1st order reflection from the stage boundary narrows when the S-R distance increases. The source to receiver relationship study shows that the approach of the EEL, where the time interval is relative to the time of sound emission instead of the time of direct sound arrival, seems also valid in relation to the likelihood of arriving 1st order reflections from the stage boundary under the assumption that the emission of sound by the different sound sources is synchronised.

However, to be able to investigate the impact of early reflected sound energy at various distances, the direct sound should be omitted from the time interval (as used by the EEL). It was found that the direct sound must be omitted by using a time interval starting at 9 to 13 ms after the arrival of the direct sound to sufficiently reduce its influence to ≤ 1.0 dB. To be able to omit the direct sound, the source and receiver positions must be kept at least 2 m from any stage boundary, seating and stands. However, to be able to measure an accurate reference level at 1 m containing the direct sound and floor reflection only, no reflections may arrive before 21 ms (influence reflected sound ≤ 0.1 dB). This implies that for the reference measurement at 1 m distance, source and receiver positions must be kept at least 4 m from any stage boundary, seating and stands.

Based on these insights, it is proposed to extend the commonly used ST parameters by introducing a variable time point ‘103-delay’ that takes into account the delay of direct sound by increased distance, see equation (1) and (2), where the ‘delay’ is the S-R distance divided by the speed of sound. This way, the parameters can be measured at S-R distances up to 25 m, considering a time interval width of 30 ms as an acceptable minimum. The time interval of early reflected sound starts at 10 ms instead of 20 ms to be able to measure closer to the stage boundaries up to 2 m. Infinity is used instead of 1000 ms as an upper time limit for the late reflections because it is conceptually clearer. At 1 m distance, the parameters are similar to the ISO 3382-1:2009 parameters.

$$\mathrm{ST}_{\mathrm{early,d}} = 10\lg\left(\frac{\int_{10}^{103-\mathrm{delay}} p_d^2(t)\,\mathrm{d}t}{\int_0^{10} p_{1m}^2(t)\,\mathrm{d}t}\right) \quad [\mathrm{dB}], \tag{1}$$

$$\mathrm{ST}_{\mathrm{late,d}} = 10\lg\left(\frac{\int_{103-\mathrm{delay}}^{\infty} p_d^2(t)\,\mathrm{d}t}{\int_0^{10} p_{1m}^2(t)\,\mathrm{d}t}\right) \quad [\mathrm{dB}], \tag{2}$$

where $\mathrm{ST}_{\mathrm{early,d}}$ = Early Support at distance d [dB], $\mathrm{ST}_{\mathrm{late,d}}$ = Late Support at distance d [dB], p_d = Sound pressure measured at distance d [Pa], p_{1m} = Sound pressure measured at 1 m distance [Pa], delay = S-R distance divided by the speed of sound [ms].

Furthermore, it is recommended to use 1.0 meter transducer heights and to perform the measurements on a stage occupied with chairs and stands. The extended ST parameters should be determined as an average over 5 measurements, while rotating a dodecahedron loudspeaker in steps of 72 degrees. A decay range INR of at least 45 dB is recommended for all measured RIR’s on stage.

It is expected that $\mathrm{ST}_{\mathrm{early,d}}$ is a valuable parameter to investigate the contribution of early reflections to ensemble playing with increasing source–receiver distance. It is likely that stages exists where $\mathrm{ST}_{\mathrm{early}}$ measured at 1 meter S-R distance is relatively high, suggesting good support from early reflections for the own instrument, while $\mathrm{ST}_{\mathrm{early,d}}$ at 10 meters S-R distance is relatively low, suggesting poor support from early reflections for sound from the other players. In such cases, $\mathrm{ST}_{\mathrm{early}}$ measured at 1 meter S-R distance only may not be sufficient in describing stage support.

In contrary, it is expected that $ST_{late,d}$ is not dependant on the S-R distance. In a theoretical diffuse sound field, the sound level is not dependant on the S-R distance outside the critical distance. By the $ST_{late,d}$ the energy of the late part of the impulse response is measured using a time interval relative to the time of sound emission. This implies that, if reflections after 103 ms are considered as diffuse reflections, the (average) energy from these reflections may be equal for any S-R distance.

However, it must be investigated whether $ST_{early,d}$ is a reasonable indicator for the subjective impression of ensemble playing at various distances. Such an investigation should also reveal preferred values for $ST_{early,d}$. So far, the research presented in this paper is limited to the metrological aspects of stage acoustic parameters and subjective evaluations are considered as future work. In the next section, the impact of using the variable time interval instead of using fixed time intervals as described in section 2.6 is investigated for measurements on various concert hall stages. Besides that, the advantage of the $ST_{early,d}$ and $ST_{late,d}$ is investigated through evaluation of the different concert hall stages.

5. The effect of the time interval choice in measured stage acoustic parameters

5.1. Method

The effect of the time interval choice in stage acoustic parameters on measured results has been studied for eight different concert hall stages with various conditions. On all stages impulse response measurements have been performed using a comparable measurement method and equal source–receiver layout for optimal comparison. From these impulse responses the sound level L_{a-b} has been calculated using Dirac 5 for different time intervals $a - b$ at various distances d relative to the sound level of the direct sound + floor reflection at 1 m distance in the 0–10 ms interval corresponding to the ST parameters, see equation (3). All values have been arithmetically averaged over 250 to 2000 Hz octave bands.

$$L_{a-b} = 10\lg\left(\frac{\int_a^b p_d^2(t)\,\mathrm{d}t}{\int_0^{10} p_{1m}^2(t)\,\mathrm{d}t}\right) \quad [\mathrm{dB}]. \tag{3}$$

Based on the findings as reported in the previous sections there are two time boundaries which connect the three important time intervals direct, early reflected and late reflected sound. The time points 5, 7, 10 and 20 ms have been used in [19, 23], [18, 15, 22], [3, 4] and [3, 4] respectively to describe the transition time point between the direct sound and the early reflections which will be denoted 'x'. The time points 40, 50, 80 and 100 ms have been used in [22], [15], [3, 4, 19] and [3, 4, 18] respectively to describe the transition time point between the early reflections and late reflections and will be denoted 'y'. Other relevant time points are 0 ms, which is defined as the arrival time of the direct sound. Finally, the variable time point denoted 'var' will be used which is defined as the

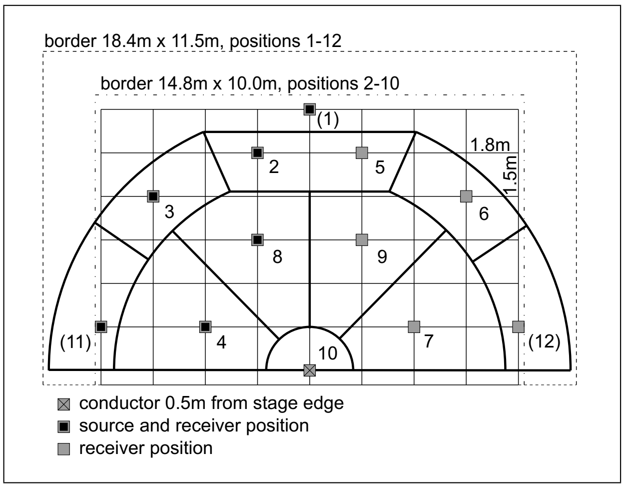

Figure 4. Measurement positions layout.

time point of 103 ms minus the delay between the time of sound emission from the source and the time of direct sound arrival at the receiver as proposed in the extended ST parameters in section 4.

An overview of the concert hall stages that have been used is given in Table III. During the 2009 tour by the Dutch Student Orchestra NSO, stage acoustic measurements have been performed in 7 Dutch halls (halls A to G). Additional measurements have been performed in one of these halls after refurbishment where the seats were replaced and a canopy was installed (hall E+). Also, measurements were performed during a refurbishment of hall C at the time that no seats were installed in the audience area (hall C-). Finally, measurements were performed in a concert hall, where a canopy was installed (hall H+) that could be lifted to the ceiling (hall H). The stages were empty during the measurements (except hall A were this was not possible). All seats and stands were removed to save time during the measurements and to be able to use the exact same source and receiver positions on all stages.

A measurement layout with fixed source and receiver positions was developed to match the positioning of instrument groups in a symphonic orchestra, illustrated in Figure 4. The source and receiver positions are put on a rectangular grid of 1.5 m by 1.8 m with a 2 m border around the outside positions to avoid reflections arriving before 10 ms. The positions represent the following instrument sections or persons: 1: timpani or percussion, 2: woodwinds left, 3: horns, 4: 1st violins, 5: woodwinds right, 6: brass, 7: celli, 8: 2nd violins, 9: viola, 10: conductor, 11: 1st violins back row or harp, 12: double basses. The size of the layout for halls A to G was 14.8 m deep and 11.5 m wide, so all positions 1 to 10 would fit. Positions 11 and 12 were later added to the layout for the measurements on stage H which is wider, however in this hall position 1 could not be used because of the limited stage depth.

Because of the symmetry of the layout and of most halls and stages, only 6 positions need to be both source and receiver positions and 6 positions are only receivers. Also, for source position 1 only half of the receivers

Table III. Concert hall stage properties. * Stage A is not a rectangular stage, so width and depth are presented in a range. ** During the measurements all seats were unoccupied. C/R/S: Canopy / Reflectors / Shell; CoS: Chairs on Stage.

hall	width (m)	depth (m)	height (m)	Area (m^2)	C/R/S	CoS	Seats**	RT_{unocc}	Volume [m^3]
A*	7–20	4–12	15.5	150	–	Yes	2000	2.3	19,000
B	16.4	11.2	13	240	S+R	No	1450	2.0	11,500
C	18.0	11.5	21	210	R	No	1250, old	2.0	14,400
C-	18.0	11.5	21	210	R	No	No seats	4.0	14,400
D	20.4	13.7	17	260	R	No	1900	2.0	15,500
E	17.4	11.7	15	210	–	No	2200, old	2.4	27,700
E+	17.4	11.7	10.4	210	+C	No	2200, new	2.9	27,700
F	21.6	17.5	8.5	390	Large S	No	900	1.7	12,000
G	17.5	12.6	18	220	–	No	1050	2.3	16,500
H	22.0	10.5	16.0	231	–	No	1400	2.4	17,500
H+	22.0	10.5	9.1	231	+C	No	1400	2.4	17,500

have to be measured. Measurements are performed at 1 m distance for all source positions. In total, this results in $5 \times 12 + 1 \times 7 = 67$ S-R pairs. In the NSO project only source positions 1 to 4 were used to save time (36 S-R pairs). The 1 m distance measurement was performed with one microphone in front of the sound source and a second microphone and the right side (seen from the audience area). For optimal comparison of all stages A-H the positions 11 and 12 are not used in this research, resulting in a mutual S-R distance between 1 and 10.6 meters and on average 5.3 meters. It was found that the S-R distance was kept within 0.15 m accuracy.

For every S-R pair, 4 impulse responses have been measured using room acoustic measurement software Dirac and a 5 s exponential sweep signal while rotating the B&K type 4292 sound source in equal steps of 90 degrees. The rotation of the sound source is done to correct for directivity deviations, which is a problem when measuring close to a dodecahedron shaped sound source (recent research has shown that actually 5, 7 or 8 equal angular steps result in a considerable reduction of uncertainty [16]). Care was taken that the Impulse to Noise Ratio [20] of all measured impulse responses was > 45 dB for all frequency bands of interest. All transducers were put at a height of 1.3 m in accordance with ISO 3382-1:2006. Except for stage A, no chairs were on the stages that could have influenced the 1 m distance measurement. Care was taken that the two different microphones had their own reference measurement at 1 m distance.

5.2. Direct sound and early reflected sound at 1 m S-R distance

First, the influence of the direct sound and floor reflection is investigated on results of the various proposed early reflected sound time intervals measured at 1 m distance using equation (3). Figure 5 shows the average value for all possible variations L_{x-100} including L_{0-100} for every sound source position and receiver position at 1 m distance from that source position. Due to the likely influence of the chairs on stage, hall A is excluded in the average. At the source position S4 which is furthest away from any stage boundary the average difference between

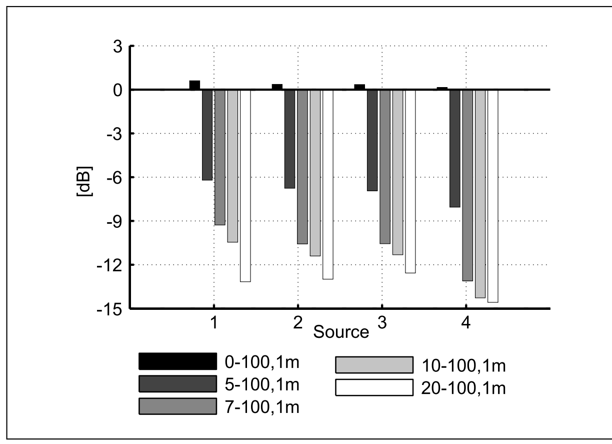

Figure 5. Halls B-H+ average value for all possible variations L_{x-100} and L_{0-100} per source position.

L_{10-100} and L_{20-100} is less than 0.3 dB. Similar results were found at S1, S2 and S3 for large stages E and F, but on average the difference increases up to 2.7 dB for S1, which is most often in close proximity to stage walls. This suggests that the time interval 10–20 ms is sensitive to very early arriving reflections and it confirms that these very early reflections can be measured without considerable influence from the direct sound and floor reflection as was concluded in section 3.5. The average difference between L_{7-100} and L_{10-100} is 1.0 dB for all source positions while the average difference between L_{5-100} and L_{10-100} is 4.9 dB. It is very likely that in the L_{5-100} and L_{7-100} (part of) the energy from the direct sound and/or floor reflection is included in the measurement at 1 m distance. As a result, the later reflections are partly masked by the direct sound. However, the results confirm that the time interval to capture the early reflected sound needs to start at 10 ms to be able to take into account reflections from close by stage boundaries (between 2 and 4 m) distance at all positions.

5.3. Direct sound and early reflected sound at all source–receiver distances

Secondly, the influence of the direct sound and floor reflection on results of the various proposed time intervals for early reflected sound measured at various distances is investigated. To be able to do so, trend lines of parameter values over distance for all possible variations L_{x-40} including L_{0-40} have been calculated for every hall. An example of the relation between the individual parameter values and the trend line are shown in Figure 6. The trend line is determined using a least squares fitting of a logarithmic relation $y = a\lg(x) + b$. For every trend line the correlation coefficient R^2 is calculated, which describes the fraction of variation in y that is explained by its relationship with x.

An upper time limit of 40 ms is chosen to make the parameters as sensitive as possible to changes in the lower time limit. The results of these trend lines are presented in the first column of graphs in Figure 7. The average correlation between the parameter value and the distance is very strong for L_{0-40} ($R^2 = 0.95$) in all halls, strong for L_{x-40} in hall A ($R^2 = 0.80$), moderate for L_{x-40} in halls D-H ($R^2 = 0.20$) and weak for L_{x-40} hall B, C and C- ($R^2 = 0.03$). The trend line for L_{5-40} is calculated without the 1 m distance measurements, because their results deviate too much from the trend after 1 m. The results for L_{0-40} ms for all halls are almost equal and it can be seen that per hall the parameters L_{5-40}, L_{7-40} and L_{10-40} are very similar and only differ slightly closer to the sound source. But in most cases L_{20-40} is considerably lower, except for the largest stage F. It appears that on stage F little sound energy arrives in the time interval 5–20 ms. This suggest that the increase of L_{5-40} and L_{7-40} close to the source may be caused by influence from the direct sound and floor reflection, which is also the case for some other stages. However, on all other stages it appears to be necessary to include at least the 10–20 ms time interval to measure all early reflected sound (although this may influence the parameter value less when using a higher upper limit than 40 ms). Also, the results confirm that it is necessary to omit the direct sound and floor reflection to be able to measure differences between different halls as was suggested by many other researchers, see section 2.6.

5.4. Early reflected sound at all source–receiver distances

Based on the previous results the influence of the upper time limit for early reflected sound is further investigated using a 10 ms lower time limit. The trend lines of parameter values over distance for all possible variations L_{10-y} including $L_{10-\mathrm{var}}$ have been calculated for every hall, see the second column of graphs in Figure 7. The parameter $L_{10-\mathrm{var}}$ is drawn as a dashed line without a label. The average correlation between all parameter values and the distance is very strong for hall A ($R^2 = 0.86$) and very weak for hall C ($R^2 = 0.04$). For the other halls, the average correlation increases with the size of the temporal window: $R^2 = 0.15, 0.28, 0.39, 0.41$ for L_{10-40}, L_{10-50}, L_{10-80}, L_{10-100} respectively. This implies that, although the trend lines for all parameters seem to be more or less parallel, the deviations of the individual measurements from the logarithmic trend line are smaller with increasing size of the temporal window. In the parameter $L_{10-\mathrm{var}}$ the temporal window size is made dependant on the S-R distance using the variable upper time limit ‘103-delay’. Although the $L_{10-\mathrm{var}}$ trend line appears almost equal to the L_{10-80} trend line, the correlation to a logarithmic fitted trend line increases from moderate for L_{10-80} ($R^2 = 0.39$) to strong for $L_{10-\mathrm{var}}$ ($R^2 = 0.49$).

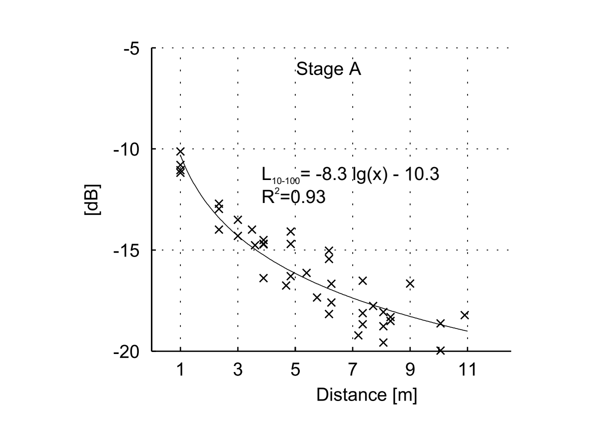

Figure 6. Example of the relation between the individual L_{10-100} parameter values and the trend line for stage A.

In Figure 8a, the deviation of the average value per hall from the average value for all halls are presented for all possible variations L_{10-y} and $L_{10-\mathrm{var}}$ for all S-R combinations. Also, the average deviation of L_{10-100} at 1 m distance is included. It is shown that the difference in ranking between the halls is small for all parameters measured over various distances. However, the difference between L_{10-100} at 1 m distance per hall is smaller and only hall A and hall B are more than 1 dB different from the hall average value. It is shown that the time interval choice is not critical for ranking the stages when performing measurements with various S-R distances, except for hall F with a relatively large stage. A different ranking is found between halls with various S-R distances compared to 1 m distance only.

5.5. Late reflected sound at all source–receiver distances

First, the impact of using ‘time to infinity’ instead of 1000 ms is investigated at 1 m S-R distance. For all halls, the difference between $L_{100-1000}$ and $L_{100-\mathrm{inf}}$ was calculated for the 250 to 2000 Hz octave bands. It was found that for all halls with a reverberation time $<$ 2.5 seconds and for all separate octave bands, the difference is < 0.02 dB with all files having an INR $>$ 45 dB. Two exceptions are halls E+ and C- were the difference is < 0.05 dB and < 0.17 dB respectively. It can be concluded that the difference between using 1000 ms and ‘inf’ is negligible when the noise in the RIR is sufficiently reduced (INR $>$ 45 dB).

Using the same approach as in section 5.4 the influence of the lower time limit of the late reflected sound level is investigated. The trend lines of parameter values over distance for all possible variations $L_{\mathrm{y-inf}}$ including $L_{\mathrm{var-inf}}$

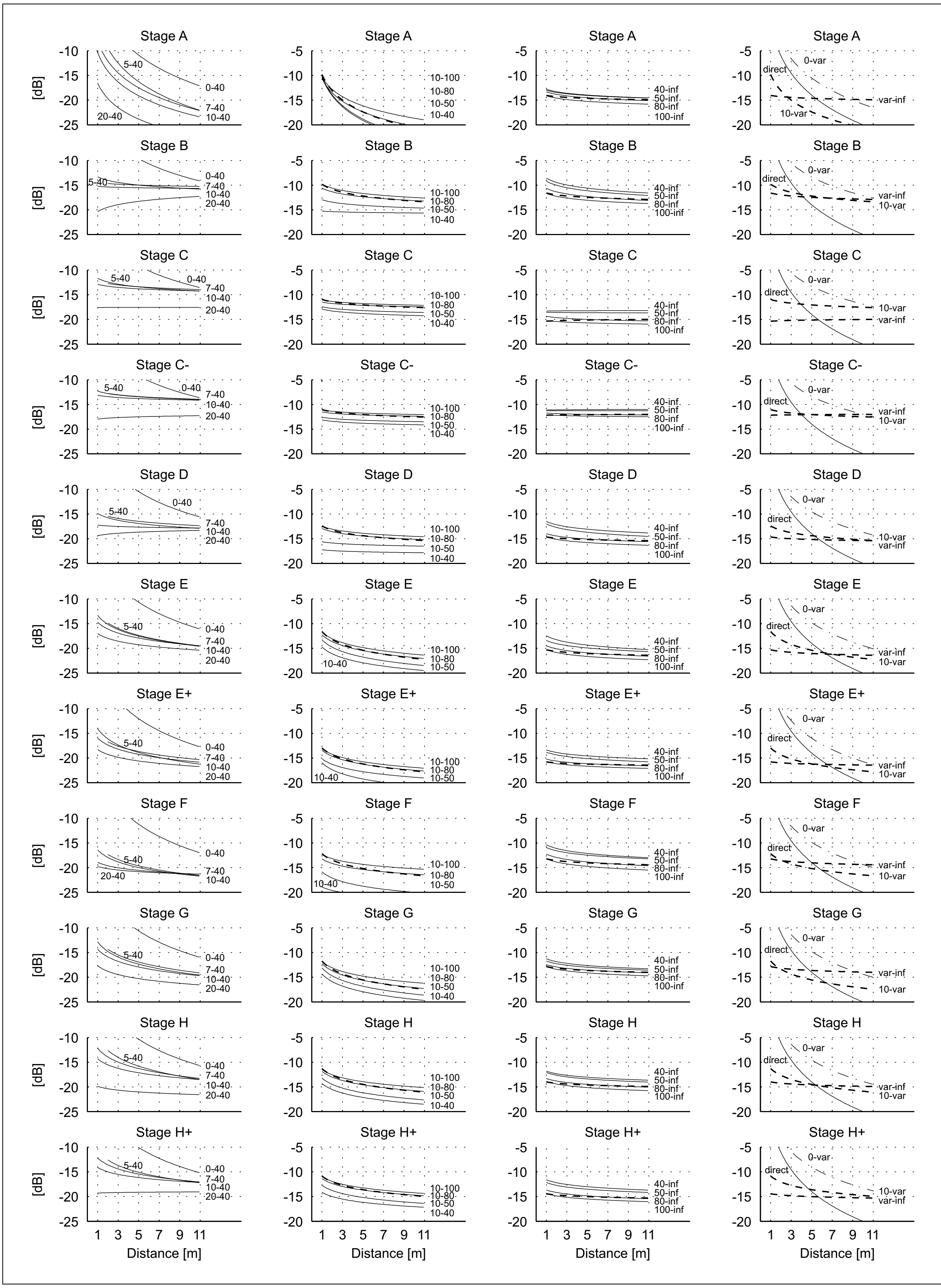

Figure 7. Variations in time intervals of L_{a-b} per distance for 11 stages; 1st column: variation in lower limit for x-40 ms; 2nd column: variation in upper limit for 10-y ms where dashed line has $y = 103 - \text{delay}$; 3rd column variation in lower limit for $y-\text{inf}$ ms where dashed line has $y = 103 - \text{delay}$; 4th column: comparison of 10-var and var-inf to 0-var and theoretical direct sound decay.

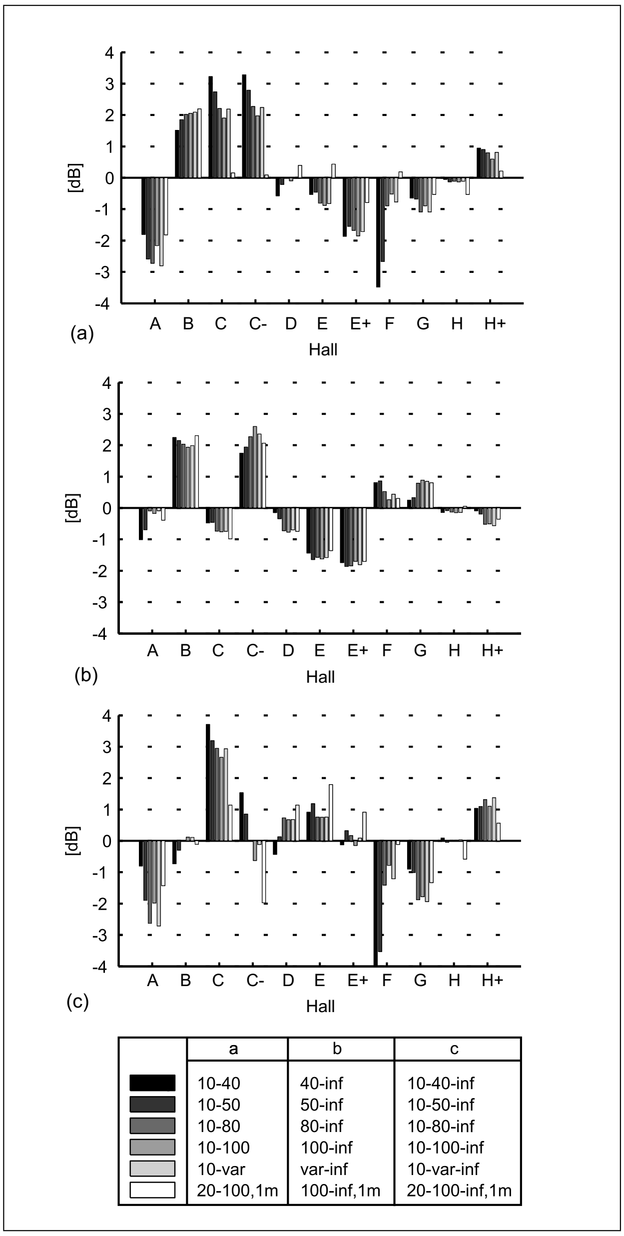

Figure 8. Average value deviation for (a) the early reflected sound level, (b) the late reflected sound level, (c) the difference between early and late reflected sound level. The reference value (0 dB) is the average value of all halls.

have been calculated for every hall, see the third column of graphs in Figure 7. The parameter $L_{\text{var}-\text{inf}}$ is drawn as a dashed line without a label. It is clear that the differences between the different parameter trend lines per stage are small and that the trend lines seem parallel. The $L_{\text{var}-\text{inf}}$ ($R^2 = 0.24$) shows weaker correlation with distance than the other parameters $L_{\text{y}-\text{inf}}$ ($R^2 = 0.50$ for all $L_{\text{y}-\text{inf}}$ parameters), except for stage C, where $L_{\text{var}-\text{inf}}$ shows a slight increase per distance and the other parameters $L_{\text{y}-\text{inf}}$ are almost flat ($R^2 < 0.10$).

In Figure 8b, the deviation of the average value per hall from the average value for all halls are presented for all possible variations $L_{\text{y}-\text{inf}}$ and $L_{\text{var}-\text{inf}}$ for all S-R combinations. Also, the average deviation of $L_{100-\text{inf}}$ at 1 m distance is included. It is shown that the difference in ranking between the halls is again small for all parameters measured over various distances as well as the 1 m. Also, it is shown that the time interval choice is not critical for ranking the stages and results from measurements at 1 m distance are similar to results with various S-R distances.

5.6. Balance between Early and Late reflected sound at all source–receiver distances

To study the balance between early and late reflected sound level, the difference between $L_{10-\text{y}}$ and $L_{\text{y}-\text{inf}}$ was calculated denoted $L_{10-\text{y}-\text{inf}}$. In Figure 8c, the deviation of the average value per hall from the average value for all halls are presented for all possible variations $L_{10-\text{y}-\text{inf}}$ and $L_{10-\text{var}-\text{inf}}$ for all S-R combinations. Also, the average of $L_{10-100-inf}$ at 1 m distance is included. It appears that the ranking between the halls more strongly depends on the choice of time limit ‘y’. This is mainly caused by the influence of hall F on the results. When hall F is omitted from the data, the influence of time interval is comparable to the early and late reflected sound level separately.

6. Evaluation of different stages

Although the time interval choice seems to be not very critical for comparing average stage values, the highest correlation to a logarithmic trend line was found for the early reflected sound level using $L_{10-\text{var}}$, which is equal to the $\text{ST}_{\text{early,d}}$ as defined in section 4. This implies that the use of a variable time interval is most suitable to describe the decay of early reflected sound over distance. On the contrary, in theory the late sound level was expected to vary little over distance as in a diffuse sound field. The lowest correlation to a logarithmic trend line for the late reflected sound level is found for $L_{\text{var}-\text{inf}}$, which is equal to the $\text{ST}_{\text{late,d}}$ as defined in section 4. This suggest that a variable time interval is also most suitable to describe the late reflected sound level. To further study the relation between early and late reflected sound level $L_{10-\text{var}}$ and $L_{\text{var}-\text{inf}}$ are presented in the fourth column of graphs in Figure 7. Besides that, the early reflected sound level including direct sound and floor reflection is presented denoted $L_{0-\text{var}}$ (which is similar to the original EEL) and the theoretical direct sound level decay based on a 6 dB decrease per distance doubling for a monopole.

It is shown that the $L_{0-\text{var}}$ is comparable for all halls, especially closer to the sound source, while the $L_{10-\text{var}}$ and $L_{\text{var}-\text{inf}}$ are clearly different per hall. On stage A, F and G the late reflected sound level is higher than the early reflected sound level at S-R distance > 2 m. For stage A and G this can be explained by the mainly absorptive stage surroundings existing of sloped seating areas. Stage F has fewer early arriving reflected sound energy as a result of the large dimensions compared to the other stages. On stages B, D, E, and H the early and late sound level is more or less equal, although on stage B both early and late sound is louder compared to stages D, E and H. The designs of stages D, E and H are similar, having a reflective wall surrounding the stage without any horizontal reflectors above the stage (the reflectors in hall D are tilted and reflect the sound from the stage towards the audience area). The overall increase in reflected sound level in hall B is probably caused by the smaller volume of the space compared to the halls D, E and H and the shell shaped stage. Stage C appears to be a clear outlier where the early reflected sound level is at least 3 dB higher than the late sound for all distances. This might be explained by the highly sound diffusing walls and downwards tilted reflective balcony-edge surrounding the stage combined with the two reflectors above the stage. Together, these applications seem to provide a large amount of early reflected sound energy on stage. The difference between stage C and C- illustrates that the early reflected sound does not change, when the acoustics of the hall changes, while the late reflected sound increases by approx. 3 dB. In hall H, the addition of the canopy increases the early reflected sound level by approx. 1 dB while the late reflected sound decreases approx. 0.5 dB, so effectively increasing the early to late difference by 1.5 dB. These effects are not found in hall E with and without a canopy, which might be caused by this canopy being zigzag shaped and partly acoustically transparent.

Interviews with several professional musicians and conductors showed that there seems to be a general agreement that hall A and F have a very poor reputation in terms of stage acoustics while stages B and C have a very good reputation. Judgments on other halls' stages are less distinct. The measurement results are well in line with these judgments as it is generally accepted that stages with high early reflected sound energy are favored over stages with less low early reflected sound energy. However, in these particular cases it can be concluded that ST_{early} at 1 m distance does not fully predict this outcome while $ST_{early,d}$ assessed over various distances does. It is notable that even though ST_{late} is relatively high in hall B, possibly causing masking part of the direct and early reflected sound, this stage is still one of the musicians favorites.

7. Discussion

This paper has provided a detailed analysis of relevant metrological issues concerning stage acoustic measurements resulting in a proposal to optimise and extend the existing ST_{early} and ST_{late} parameters so they can be measured at various source-receiver distances, see section 4. While this study has provided several new insights, it is also important to mention the limitations of this study:

- The study did not investigated whether $ST_{early,d}$ is a reasonable indicator for the subjective impression of ensemble playing at various distances.
- The study did not establish preferred values for $ST_{early,d}$ at various distances.
- The study checked the theoretical assumptions based on measurements on empty stages without chairs and stands. Theoretical assumptions were only checked for concert hall stages and results may only count for stages close to the surveyed ones.

In spite of these shortcomings, the present study provides an optimal time interval to measure early and late reflected sound energy at various source–receiver distances on stage based on existing and new insights. To the best of our knowledge it is for the first time, that it has been demonstrated that the amount of early reflected sound energy on stage is distance dependant and correlates strongly to a logarithmic trend line using a variable time interval, while the amount of late reflected sound energy is not clearly dependant on the distance. Also, a variable time interval has not been reported in previous studies. Future work should focus on

- Exploring the influence of chairs, risers, stands, screens and persons on stage on the parameter results.
- Exploring the influence of the actual instrument directivity [33] compared to the omnidirectional sound source directivity.
- Exploring the impact of separate architectural applications like stage walls, diffusers and reflectors on the parameter results.
- Finally, it should be investigated whether $ST_{early,d}$ correlates with the subjective impression of ensemble playing and whether the balance between $ST_{early,d}$ and $ST_{late,d}$ may be a relevant descriptor of the early reflections masking by reverberation at all distances on actual stages.

8. Conclusions

Different time interval limits have been proposed for the stage acoustic parameters but there is no agreement on the preferable limits. Also, there is a growing interest to measure stage acoustic parameters at various source to receiver distances. In this research, a detailed analysis of relevant metrological issues concerning stage acoustic measurements has lead to the optimised and extended $ST_{early,d}$ and $ST_{late,d}$ parameters that can be measured at various source–receiver distances using a variable time interval of '103-delay'. Theoretical assumptions were checked and confirmed based on systematic analyses of measured results for different concert hall stages with various conditions and various source to receiver distances. It can be concluded that different time interval limits did not result in a different ranking of the measured stages. However, it was shown that measurements of early reflected sound energy using $ST_{early,d}$ at various source–receiver distances is complementary to the common ST_{early} measured at 1 m distance, resulting in clearer discrimination between these measured stages.

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