Acta Acustica 2023, **7**, 20
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https://doi.org/10.1051/aacus/2023015

Available online at:
https://acta-acustica.edpsciences.org

Topical Issue - The Sound of Ancient Theatres

SCIENTIFIC ARTICLE OPEN ACCESS

A note on meaningful acoustical parameters for open-air theatres

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Received 12 January 2023, Accepted 13 April 2023

Abstract – The acoustics of performance spaces are usually characterized by the reverberation time and a handful of other acoustical parameters defined in ISO 3382-1. However, these parameters have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theatre. The lack of late reflections means that the decay curve is often far from a straight line, and the reverberation parameters turn out to be unreliable. Also, parameters that use the balance between early and late reflections are problematic when late reflections are more or less absent. It is necessary to rethink the need for acoustical parameters instead of sticking to the well-established parameters meant for concert halls. The most important acoustical features of a theatre are that speech is sufficiently loud and clear, which can be described by acoustical parameters for strength and clarity. In addition, it is important to avoid echoes, which are more likely to appear in an outdoor environment than in a room. Thus, there is a need for an objective echo parameter. Acoustical parameters that vary strongly with receiver position are not well suited for a global characterization of the acoustics of a space. For this purpose, a parameter for the acoustical efficiency is suggested; it is defined as ten times the logarithm of the total sound energy in the impulse response relative to the energy of the direct sound. The spatial average of this parameter can be used for comparison of the acoustics of different open-air theatres.

Keywords: Acoustical parameters, Sound strength, Speech, Echo, Greek theatres

1 Introduction

Reverberation time and some other acoustical parameters have been well established for the characterization of the acoustics of performance spaces, ISO 3382-1 [1]. Since the reverberation time normally has small spatial variation within a room, the position averaged reverberation time works well as a global descriptor of the acoustics of closed rooms. Other parameters like EDT, sound strength and clarity are useful to describe the specific acoustical conditions in different parts of the audience area. However, these parameters have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theatre. The acoustics of an open-air theatre are very different from those of a closed room, and for that reason it is necessary to rethink the need for acoustical parameters.

Since antiquity, the most important acoustical features of a theatre are loudness and clarity of speech, avoiding disturbing echoes (see Vitruvius [2], 5.3.7). Echo problems are more likely to occur in an outdoor environment where the reflection density is much lower than in a room. Another difference between an open-air theatre and a room is that in the former, the acoustics are much more dependent on the source position, which was also well known in antiquity (see Vitruvius [2], 5.8.1–2). The theatres dealt with in the present paper are open-air theatres as those from the Greek Classical and Hellenistic period, but may also apply to many modern open-air theatres. Roman theatres were originally built to be more reverberant because of the high scene building connected to the surrounding colonnade.

The ERATO project (2003–2006) dealt with virtual reconstructions of Roman theatres and odea, and thus more reverberant spaces than the Greek open-air theatres [3, 4]. The applied acoustical parameters were reverberation time T_{30}, EDT, strength G, clarity for music C_{80}, speech transmission index STI and the Dietsch echo parameter. Reconstructed sounds included both speech and music. It was found that echo problems could appear in some places in the reconstructed theatres.

Although the reverberation time is often considered the most important room acoustical parameter, several researchers have found that decay parameters (reverberation time and EDT) are not suitable for open-air theatres [5–10].

Another acoustical parameter that has been applied by some researchers is the direct-to-reverberant ratio (DRR) (see Bo et al. [11]). This is based on ideas that go back to very early studies on listening in reverberant sound fields.

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Whether this parameter could be meaningful in an open-air theatre will be discussed below.

The current article is based on a presentation for the 2nd symposium on Acoustics of Ancient Theatres in Verona, 2022 [12]. However, the contents have been extended and several new parts have been included in this article. Also, the examples have been changed and expanded. The acoustical parameters are analysed through computer simulations using the ODEON combined software, version 17.14.

2 Parameters for measurements

Acoustical parameters suitable for measurements should preferably meet the principles in ISO 3382-1 [1], which implies a sound source that is omni directional and parameters derived from the impulse response in octave bands at least covering the six bands from 125 Hz to 4000 Hz.

2.1 Impulse response

First, some details of the impulse response are considered. The virtually reconstructed Greek theatre in Epidaurus is used as an example. Figure 1 shows the plan of the theatre with reconstructed scene building and indication of four source positions, named A, B, C, and D. The height is 1.5 m above the “floor”. Although it is common praxis to measure acoustical parameters in a hall without the audience, it is thought that for an open-air theatre it is more relevant to investigate the acoustics of the theatre as in use, i.e. with an audience. This also implies, that the details of the seat rows and related possible diffraction effects from the edges of the empty seat rows are neglected here. The audience areas are modelled with sound absorbing surfaces that simulate a seated audience on hard chairs and with a mid-frequency scattering coefficient of 0.70.

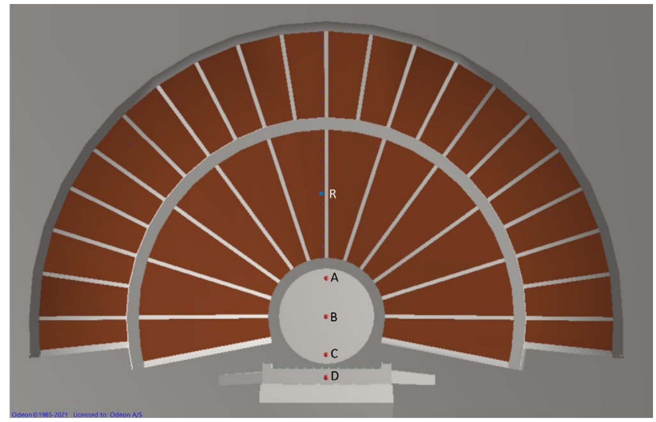

Figure 1. The ODEON model of the reconstructed Epidaurus theatre seen from above. The scene building is reconstructed and the audience areas are shown in brown. Four source positions are indicated; A in front of the orchestra, B in centre of the orchestra, C on orchestra in front of the scene building, and D elevated on the proscenium. The receiver position used for the results in Figure 2 is indicated with R.

The impulse responses are studied in a receiver position near the middle of the audience area. The squared impulse responses shown in Figure 2 are from four different source positions marked A, B, C, and D in Figure 1. It is characteristic in all cases that there are very few early reflections, and there is a gap between the direct sound and sound reflections. Depending on source position, this time delay gap can be below or above 50 ms, and in the latter case the reflection may be detected as an echo, as will be discussed further below.

Figure 2 shows that the integrated squared impulse responses are very irregular over the initial 15 dB, due to the time delay gap and low reflection density. The consequence is that it makes no sense to derive the slope of the initial 10 dB, as needed for the EDT (early decay time). According to ISO 3382-1 [1] the EDT shall be determined from the slope of a linear regression of the upper 10 dB of the Schroeder curve. However, this has been shown to be a very unreliable method in cases with a strong direct sound, and as an alternative it has been suggested to derive EDT from the slope of a line connecting the starting point at 0 dB with the −10 dB point on the Schroeder curve (see Fürjes [13]). Still, it is questionable whether this is a meaningful parameter in an open-air theatre.

Other reverberation parameters like T_{20} are also highly problematic, because the start of the evaluation range (5 dB below the maximum) is not well defined when the impulse response looks like the examples in Figure 2. It might be possible to derive a reverberation time for the late part of the decay curve, starting 15 dB or 20 dB below the maximum, but it is questionable what meaning such a late reverberation should have? For the audience during a performance, particular attention is given to the beginning portion of the decay curve, and the late reverberation may not be audible (see Meyer [14], p. 189).

As a test case, acoustical parameters were calculated from the simulated impulse responses in the reconstructed Epidaurus theatre in the four source positions A through D (see Fig. 1). Twenty evenly distributed receiver positions along the central axis were used, covering the range from the first to the last seat row. For each of the source positions, the average value and standard deviation of acoustical parameters are shown in Table 1. The results are for the octave band with centre frequency 1 kHz. These calculations were made with 500 000 rays and 1000 ms length of impulse responses, resolution of impulse responses set to 3 ms, number of early scatter rays 100, and transition order 2.

In Table 1, ξ is a quality measure for the decay parameters. This is defined in Annex B of ISO 3382-2 [15] as one minus the correlation coefficient for the linear regression applied for the decay curve. The unit is ‰, and the recommended limit for a reliable reverberation parameter is $\xi \leq 10$ ‰, corresponding to a correlation coefficient $r^2 \geq 0.990$. The curvature C is another quality parameter defined in Annex B of ISO 3382-2 [15] as a measure of the deviation between T_{20} and T_{30}. The unit is % and the recommended limit for a sufficiently straight decay curve is 10 %.

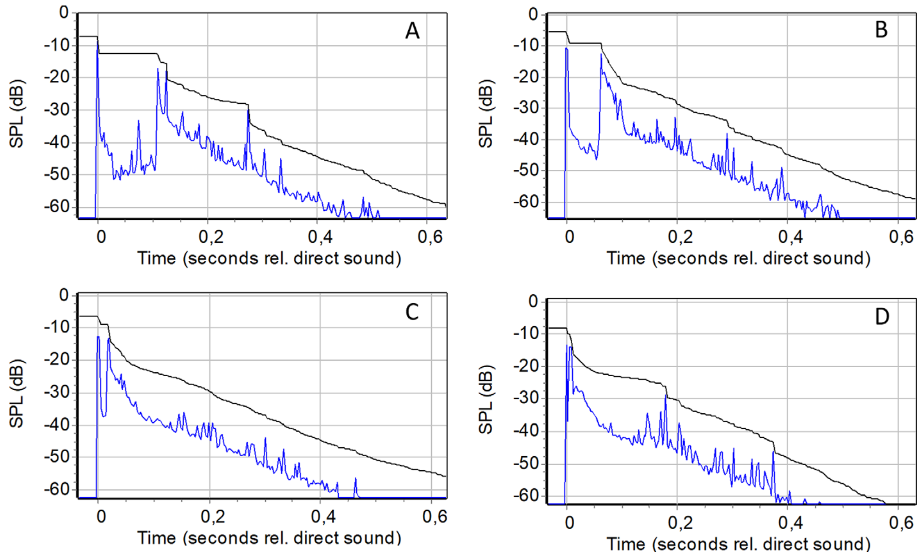

Figure 2. Simulated squared impulse responses (blue) and the integrated Schroeder curves (black) at 1 kHz octave band. This is from a reconstruction of the Epidaurus theatre with audience. The four source positions A through D and the receiver position are as shown in Figure 1.

Table 1. Example of acoustical parameters for omni source calculated in virtually reconstructed Epidaurus with audience, using four different source positions and 20 receiver positions. Average and standard deviation of each parameter are presented. All results are for the 1 kHz octave band.

Parameter	Source pos. A		Source pos. B		Source pos. C		Source pos. D	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
EDT (s)	3.34	2.09	1.22	0.21	0.21	0.03	0.14	0.04
ξ (EDT) (‰)	635	277	564	150	113	40	110	55
T_{20} (s)	0.66	0.19	0.59	0.07	0.80	0.06	0.89	0.15
ξ (T_{20}) (‰)	162	142	101	42	75	25	95	34
T_{30} (s)	0.68	0.05	0.76	0.12	0.89	0.08	0.9	0.06
ξ (T_{30}) (‰)	52	18	53	26	31	25	39	23
Curvature, C (%)	7	21	30	19	13	12	4	16
Strength, G (dB)	−5.3	6.3	−5.4	3.7	−5.9	3.1	−7.4	3.2
Efficiency, E (dB)	1.8	0.7	4.6	0.5	6.4	0.3	5.8	0.5
D_{50}	0.77	0.12	0.70	0.09	0.95	0.01	0.96	0.01
C_{50} (dB)	6.3	4.6	3.9	2.2	12.9	0.8	14.4	1.4
C_{80} (dB)	6.4	4.6	12.6	2.4	16.2	0.5	16.8	1.3
T_S (ms)	29	14	24	7	16	1	12	1
Echo – Dietsch	1.87	0.36	1.45	0.19	0.43	0.08	0.49	0.14

Among the parameters for clarity, not only those related to speech D_{50} and C_{50} are included. Thus, the clarity for music C_{80} is also included here.

Also shown in Table 1 are the efficiency E and the Echo-Dietsch parameter, both of which are defined below.

2.2 Reverberation parameters

The EDT varies strongly over the positions (see Table 1). The middle value reaches 3.34 s for source position A and 0.14 s for source position D. The associated ξ values are extremely high, meaning that the applied decay curves are very far from straight slopes. It is concluded that EDT is not a meaningful parameter for an open-air theatre. A similar conclusion was made by Farnetani et al. [6].

The spatial variation of the reverberation time T_{20} is quite large, which can be seen from the standard deviations of the spatially averaged values. The ξ parameter gives a clear warning that the results are unreliable. When $\xi > 10$ ‰, it means that the decay curve used for deriving the reverberation time is far from a straight line and the result should be used with caution. The results for the ξ parameter in Table 1 indicate that this condition is strongly violated in all positions. It is concluded that T_{20} is not a meaningful parameter for an open-air theatre. A similar conclusion was made by Mo and Wang [7].

2.3 Sound strength

The sound strength G is a measure of the total sound pressure level L_p relative to the free field sound pressure level $L_{p,10}$ in a fixed distance of 10 m. It is defined in Annex A.2.1 of ISO 3382-1 [1]:

$$G = 10\lg\frac{\int_0^\infty p^2(t)\mathrm{d}t}{\int_0^\infty p_{10}^2(t)\mathrm{d}t} = L_{pE} - L_{pE,10}(\mathrm{dB}), \tag{1}$$

where $p(t)$ is the sound pressure in the impulse response measured in the receiver position, and $p_{10}(t)$ is the sound pressure in the impulse response measured in the free field in the distance of 10 m from the sound source, which must be omni directional. The L_{pE} and $L_{pE,10}$ are the corresponding sound pressure exposure levels.

It is noted, that the impulse responses are integrated over the entire duration, so the details in the impulse response as a function of time do not matter for the strength. In reality, it is sufficient to set the upper limit of the integration to the time that corresponds to a 30 dB decay or longer. With modern measuring technique, the sound strength is best derived from the impulse response, although it is in fact a measure of the steady state sound field, not of the decaying sound field.

In an open-air theatre, G will vary strongly with the distance from the sound source, just like the loudness from a talking person. The results in Table 2 show standard deviations of more than 6 dB with source position A and around 3 dB with source positions B, C and D. The variation with position is expected and unavoidable in an open-air theatre. It is concluded that G is a meaningful parameter for acoustic conditions in a specific receiver position. This agrees with findings by other researchers [6, 7, 11].

2.4 Acoustical efficiency

The efficiency E in dB is the amplification of the sound provided by the theatre, defined as the total SPL minus the SPL of the direct sound alone. This is not an entirely new parameter, because a similar approach was suggested by Farnetani et al. [6], who looked at the average difference between G_m in the theatre and in a free field using the mid frequency octave bands (500 and 1000 Hz).

A reflection from a single, perfectly rigid surface doubles the sound energy, which means an efficiency of 3 dB. In an open-air theatre this parameter can typically take values between 2 dB and 8 dB, see results for the reconstructed Thorikos Greek theatre and the Aspendos Roman theatre [12]. In an open-air theatre the source position is very important and the acoustics experienced by the audience can vary significantly from one source position to another. The efficiency includes this effect.

A problem with this parameter is, how to derive the SPL of the direct sound in the measurement position. The use of time-windowing to separate the direct sound in the measured impulse response is not a reliable method in combination with octave band filtering. This is further discussed below. Instead, the efficiency can be measured or calculated with a calibrated omnidirectional sound source as for the measurement of sound strength G. Then it is possible to estimate and subtract the energy of the direct sound in any distance from the source:

$$E = 10\lg\frac{\int_0^\infty p^2(t)\mathrm{d}t}{\int_0^\infty p_d^2(t)\mathrm{d}t} = L_{pE} - L_{pE,d} = G + 20\lg\left(\frac{d}{d_0}\right)(\mathrm{dB}), \tag{2}$$

where d is the distance in metres from source to receiver and $d_0 = 10$ m. It is seen that E and G are closely related parameters. However, E does not vary so much across the audience area. While G is a measure of the sound level in a particular receiver position, E is a more global measure of how much the theatre supports and amplifies the sound from a given source position.

In Figure 3 is shown the strength G_m at mid frequencies as function of distance for each of the four source positions A through D in the reconstructed theatre of Epidauros. For comparison is also shown the direct sound alone (free field). The efficiency is by definition the level of the strength above the free field curve.

The lowest efficiency is found with source position A. Up to around 12 m distance, the strength is around 3 dB above the free field, but drops to only around 1 dB for longer distances. This is a result of the fact that with this source position, the supporting reflection from the orchestra is only possible for the closest receiver positions. Without the reflection from the orchestra the efficiency is very low.

The other three source positions show curves for the strength that are almost parallel with the free field curve, and the efficiency is best with source positions C and D, around 6 dB.

2.5 Direct-to-reverberant ratio (DRR)

An acoustical parameter that has been used by some researchers is the direct-to-reverberant ratio (DRR), which is defined as:

$$\mathrm{DRR} = 10\lg\frac{\int_0^\tau p^2(t)\,\mathrm{d}t}{\int_\tau^\infty p^2(t)\,\mathrm{d}t}(\mathrm{dB}), \tag{3}$$

where τ is the time that separates the direct sound from the reverberant sound in the impulse response, typically 2–3 ms. The DRR is assumed to correlate with the perceived distance to the sound source when listening in a room, Zahorik [16] and Larsen et al. [17].

This parameter was investigated by Bo et al. [11] using broad band measurements, and thus trying to avoid the problem of time delay of the octave band filters. However, the results revealed that this parameter has severe problems, and there was a big difference between measured and simulated results ([11], Fig. 6).

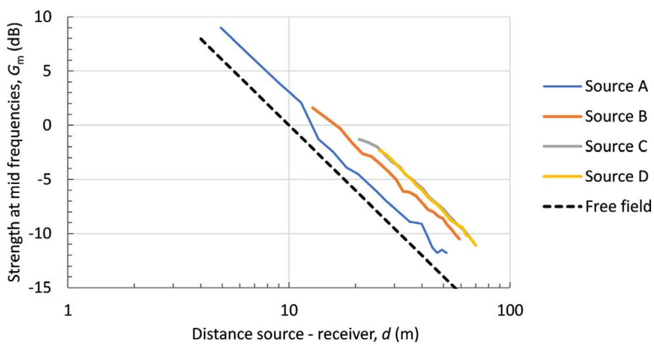

Figure 3. Strength G_m at mid frequencies (500 and 1000 Hz octave bands) displayed as function of the source–receiver distance for four source positions and 20 receiver positions.

The problems of time windowing and filtering of the impulse response are dealt with in section A.3.4 of ISO 3382-1 [1]. One of the problems is related to the determination of the start of the impulse response where $t = 0$. But the major problem occurs when windowing at a certain time in the impulse response. The best approach is doing the time windowing in the broad band impulse before the octave band filtering. The early and late components of the impulse response are filtered separately, and the integration periods are increased to include the energy delayed by the filters. This delay can be quite significant in the low frequency octave bands. In praxis it is not possible to extract the direct sound from the impulse response by time windowing.

However, for the DRR there is a way around the problem, similar to that for the efficiency described above. Instead of trying to separate the reverberant sound from the direct sound by time windowing, it is possible to apply a calibrated sound source as for the strength measurements, and then subtract the energy of the direct sound from the total energy of the impulse response:

$$\mathrm{DRR} = -10\lg\frac{\int_0^\infty p^2(t)\mathrm{d}t - \int_0^\infty p_d^2(t)\mathrm{d}t}{\int_0^\infty p_d^2(t)\mathrm{d}t} = -10\ \lg\left(10^{0,1\,G}\left(\frac{d}{d_0}\right)^2 - 1\right)(\mathrm{dB}). \quad (4)$$

It appears that DRR is closely related to G, but additional information about the distance d from source to receiver is needed. Using Equation (4) instead of Equation (3) will ensure that DRR can be measured or calculated with same accuracy as G. Previous research on DRR suffers from the problem of time windowing, and thus it remains to be seen, whether or not DRR is a relevant parameter for open-air theatres.

DRR is also closely related to the efficiency E, the difference being whether the direct sound is related to the total energy or to the reverberant energy. The latter can be rather weak in an open-air theatre, which could indicate that E is a more robust parameter that can be measured with better accuracy than DRR.

2.6 Clarity parameters

Parameters related to perceived clarity of speech are clarity C_{50} in dB, definition D_{50}, and centre time T_S in ms ([1], Sect. A.2.3). In addition, it is mentioned in a note ([1], Sect. A.2.3, Note 2) that the speech transmission index (STI) can be used to determine the intelligibility of speech.

The definition D_{50} is the ratio of the early energy up to 50 ms and the total energy in the impulse response:

$$D_{50} = \frac{\int_0^{50\,\mathrm{ms}} p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}, \quad (5)$$

where $p(t)$ is the sound pressure in the impulse response as function of the time t. It can take values between 0 and 1. In an outdoor scenario with few reflections after 50 ms, the results are typically close to 1.

The speech clarity C_{50} is similar to D_{50}, but expressed in dB and calculated as the balance between early and late energy in the impulse response, using 50 ms as the time limit. The two parameters are related as shown in Equation (A.12) in ISO 3382-1 [1]. The problem with this parameter is, that the late energy can be very small or absent in an open-air theatre, and thus C_{50} can take very high values in dB (approaching infinity), which is obviously not meaningful.

The centre time T_S is not specifically related to a speech signal, and the interpretation of the result is not obvious. It is defined Annex A.2.1 of ISO 3382-1 [1]:

$$T_S = \frac{\int_0^\infty t\,p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}(\mathrm{s}). \quad (6)$$

The centre time has the advantage of no sharp time limit as in the other clarity parameters, but it is rarely used. However, a variant of the centre time is applied in the echo parameter, to be explained below.

The speech transmission index (STI) deviates from the other parameters discussed in this section, mainly by the sound source having a directivity similar to that of a speaking person and taking the background noise into account. The measurement procedure is laid down in IEC 60268-16 [18]. The STI is intended for electroacoustic communication systems, not for room acoustics. Nevertheless, it is often applied for room acoustical cases. The popularity among acousticians may be related to the easy interpretation of the results, using five classes: bad, poor, fair, good, excellent.

However, there are problems with the STI, especially when applied to a situation with low reflection density. Onaga et al. [19] have shown that STI responds to single reflections in the same way whether the time delay

Table 2. Relationship between speech clarity parameters (mid frequencies) and the STI (average minus standard deviation) derived from measured data in a large number of rooms, Fürjes and Nagy [20].

Parameter	Quality R^2	Poor STI $\geq$ 0.30	Fair STI $\geq$ 0.45	Good STI $\geq$ 0.60	Excellent STI $\geq$ 0.75
$D_{50,m}$	0.93	$\geq$0.05	$\geq$0.30	$\geq$0.55	$\geq$0.80
$C_{50,m}$ (dB)	0.89	≥ -13	≥ -6	$\geq$1	$\geq$8
$T_{S,m}$ (ms)	0.85	$\leq$550	$\leq$ 230	$\leq$95	$\leq$40

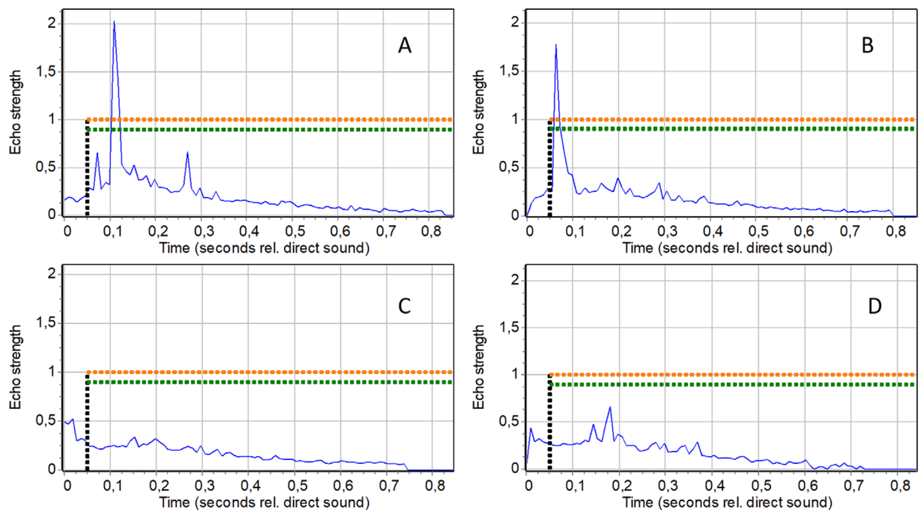

Figure 4. The echo-critical coefficient EK(τ) at 1 kHz derived from the same impulse responses as in Figure 2. The dotted black line is the time limit of 50 ms. The horizontal dotted curves represent probability of detecting a disturbing echo; 10% (green) or 50% (orange).

is positive or negative. Thus, a delayed reflection that causes a disturbing echo is not treated unfavourable in the STI. In most rooms this is not a big problem, but for an open-air theatre this is crucial and can give misleading results.

A very large amount of measured acoustical data from rooms (presumably without echo problems) were collected and analysed by Fürjes and Nagy [20]. They found quite high correlations between STI (average value minus standard deviation) and some other room acoustical parameters, especially the speech clarity parameters discussed here (see Table 2). Best correlation is for the $D_{50,m}$ parameter (mid frequency average of 500 Hz and 1000 Hz octave bands). Thus, if for example $D_{50,m}$ exceeds 0.55, it can be assumed with high certainty that STI will be greater that 0.60, i.e. in the range "Good". Similarly, the range 'Excellent' can be assumed when $D_{50,m}$ exceeds 0.80.

2.7 Echo parameter

The echo parameter was introduced by Dietsch and Kraak [21]. They derived two slightly different parameters, one for speech and another one for music. Both are related to the built-up function of the n-power centre time:

$$T_S(\tau) = \frac{\int_0^\tau t\, p^n(t)\,\mathrm{d}t}{\int_0^\tau p^n(t)\,\mathrm{d}t}\,(\mathrm{s}), \tag{7}$$

where τ is the time delay in the impulse response and for speech, $n = 2/3$. This function is compared to a fixed time interval $\Delta\tau_E = 9$ ms. The echo-critical coefficient or echo strength is:

$$\mathrm{EK}(\tau) = \frac{\Delta\, T_S(\tau)}{\Delta\, \tau_E}, \tag{8}$$

where

$$\Delta\, T_S(\tau) = T_S(\tau + \Delta\,\tau_E) - T_S(\tau). \tag{9}$$

This is the echo strength for speech, which is applied here. For music the parameters n and $\Delta\tau_E$ take different values, leading to less strict criteria for a disturbing echo.

Figure 4 shows examples of the echo strength displayed as function of the time delay. If EK(τ) exceeds 1 at a time delay $\tau > 50$ ms, there is 50 % probability that a listener will detect a disturbing echo. The maximum value of EK(τ) after 50 ms is the Echo-Dietsch parameter.

3 Parameters for simulations

For simulating an actor performing in a reconstruction of an ancient theatre, a very loud voice with clear pronunciation can be assumed. The vocal effort is between "loud" and "shouted" as defined in ANSI 3.5 [22] with A-weighted

Table 3. Average and standard deviation of acoustical speech parameters calculated in virtually reconstructed Epidaurus theatre with audience. Source positions are on orchestra in front (A) middle (B) or back (C), and on proscenium (D).

Parameter	Source pos. A		Source pos. B		Source pos. C		Source pos. D	
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
SPL(A) (dB)	54.8	6.3	53.8	3.8	52.2	2.9	51.0	2.6
STI	0.70	0.16	0.71	0.10	0.68	0.08	0.67	0.08

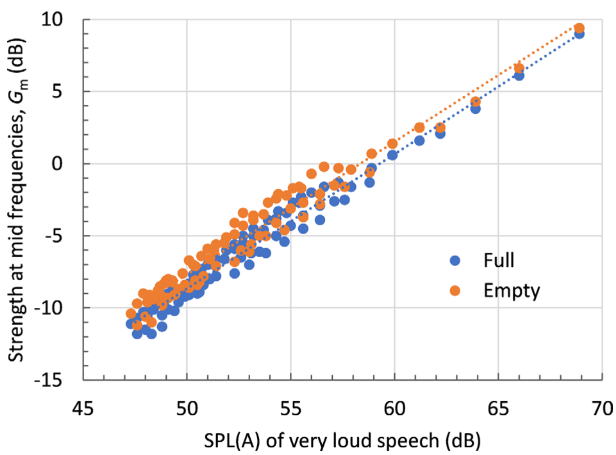

Figure 5. Relation between SPL(A) for very loud speech with full audience and the strength, G_m with full audience (blue dots) or without audience (orange dots). Results are from four source positions and 20 receiver positions.

SPL (sound pressure level) equal to 80 dB at 1 m in front of the mouth and the spectrum as "shouted". The directivity of the sound source is modelled with the data from Chu and Warnock [23].

As an example, acoustical calculations are made for the reconstructed Greek theatre in Epidaurus, including the scene building and a full audience. A speech source as described above is used and the acoustical parameters are the total A-weighted SPL and the Speech Transmission Index (STI) [18]. As in Table 1, the average over 20 receiver positions and the standard deviation are given in Table 3 for each of the four source positions.

The spatially averaged A-weighted SPLs are between 51 and 55 dB, highest in position A and lowest in position D. For comparison, the preferred median A-weighted SPL for listening to speech (in a conversation) is 52 dB for native language and 55–57 dB for second language with background noise around 40 dB (see van Heusden et al. [24]). It we transfer these findings to the situation of listening to speech from an actor in a theatre, the preferred A-weighted SPL is between 52 dB and 57 dB. Thus, with the assumed vocal effort of the actor, the calculated average speech levels in the theatre are close to ideal. The standard deviation of the variation over the audience area is quite high with source A (more than 6 dB), but relatively small with source positions C and D (less than 3 dB). When clarity and echo problems are taken into account, source position A should be avoided and the best source positions are C and D (see Table 1).

Figure 5 shows the close relationship between the A-weighted SPL of speech and the strength G_m. using an omni directional sound source. The strength is calculated with an omni directional sound source, both with and without a sound absorbing audience. In the empty theatre the results are about 1 dB higher than with a full audience. Based on the results above, it is suggested that the preferred range for G_m in the empty theatre is between −2 dB and −7 dB.

For the STI calculations, the background noise was set to 35 dB A-weighted (pink noise spectrum). The spatially averaged STI values shown in Table 3 are from 0.67 to 0.71, which is within the range corresponding to "good" speech perception. However, the STI results can be misleading, showing approximately equally good results with all four source positions. As found earlier, there are serious echo problems with source positions A and B (see Table 1 and Fig. 4), but STI does not deal with echo problems. This means that STI results are not reliable in an open-air theatre.

4 Discussion

For an overview of the acoustical results, some grid maps of calculated acoustical parameters are shown in Figures 6 through 11. Again, the four source positions A through D have been applied. For these calculations the number of rays was set to 200.000, and all other settings were as mentioned above.

In Figures 6–8 the acoustical parameters are related to loudness. The A-weighted SPL of very loud speech from a source with directivity and spectrum as a human talker is shown in Figure 6. This can be compared with the results for the strength parameter G_m using an omni directional sound source and averaging the results for the 500 Hz and 1000 Hz octave bands as shown in Figure 7. The agreement between the two sets of results is good and justify the validity of the strength parameter as a measure related to loudness. The results in Figure 8 display the efficiency parameter E_m at mid frequencies, averaging the results for the 500 Hz and 1000 Hz octave bands. This is also a kind of loudness parameter, but adjusted for the sound attenuation due to distance. So, the spatial variation is much less than in the two previous figures; note the range of the scale is only 6 dB instead of 20 dB in the previous figures. It is seen that the source positions C and D give

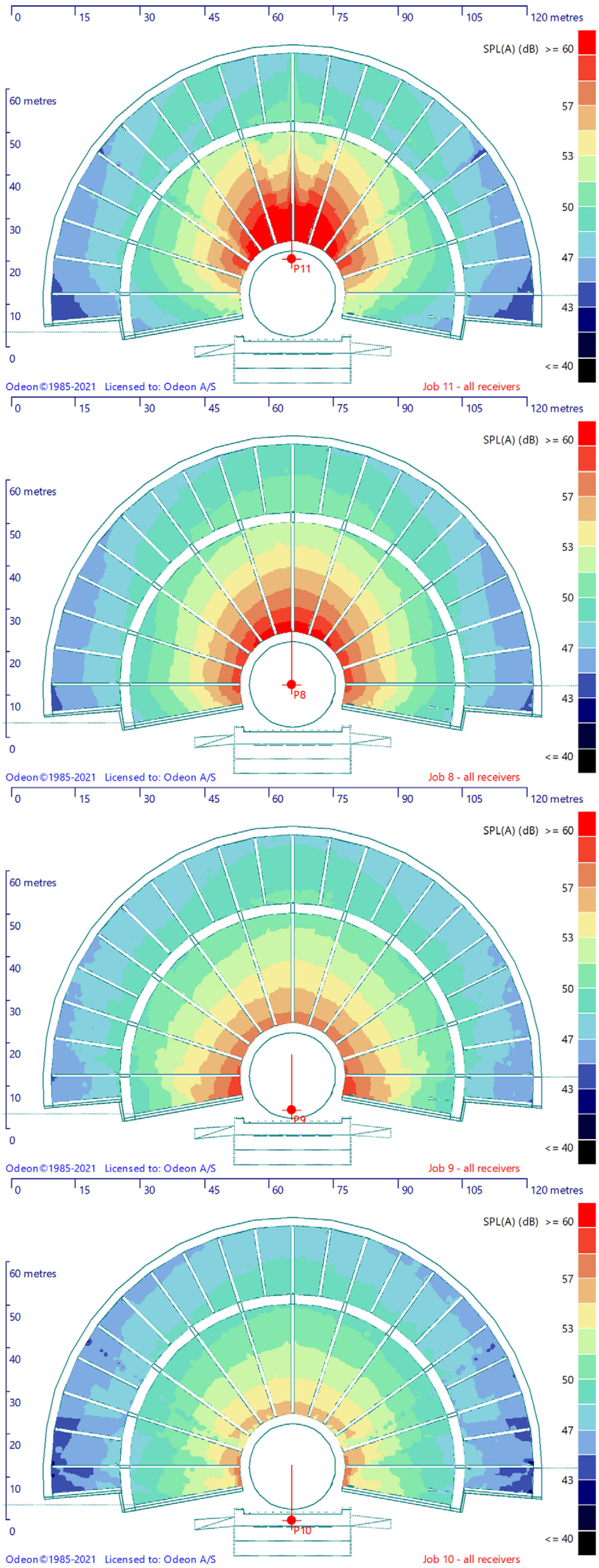

Figure 6. Grid responses of A-weighted SPL of loud speech, calculated with four different source positions.

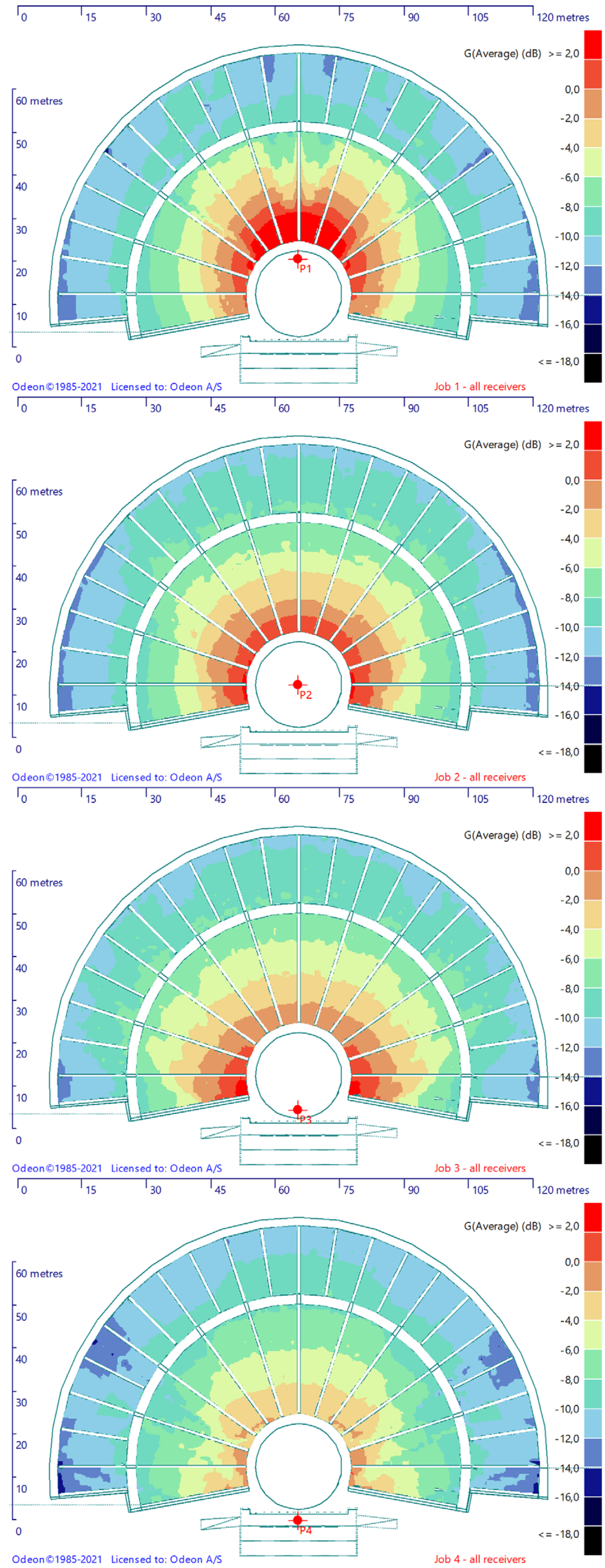

Figure 7. Grid responses of strength G_m at mid frequencies, calculated with four different source positions.

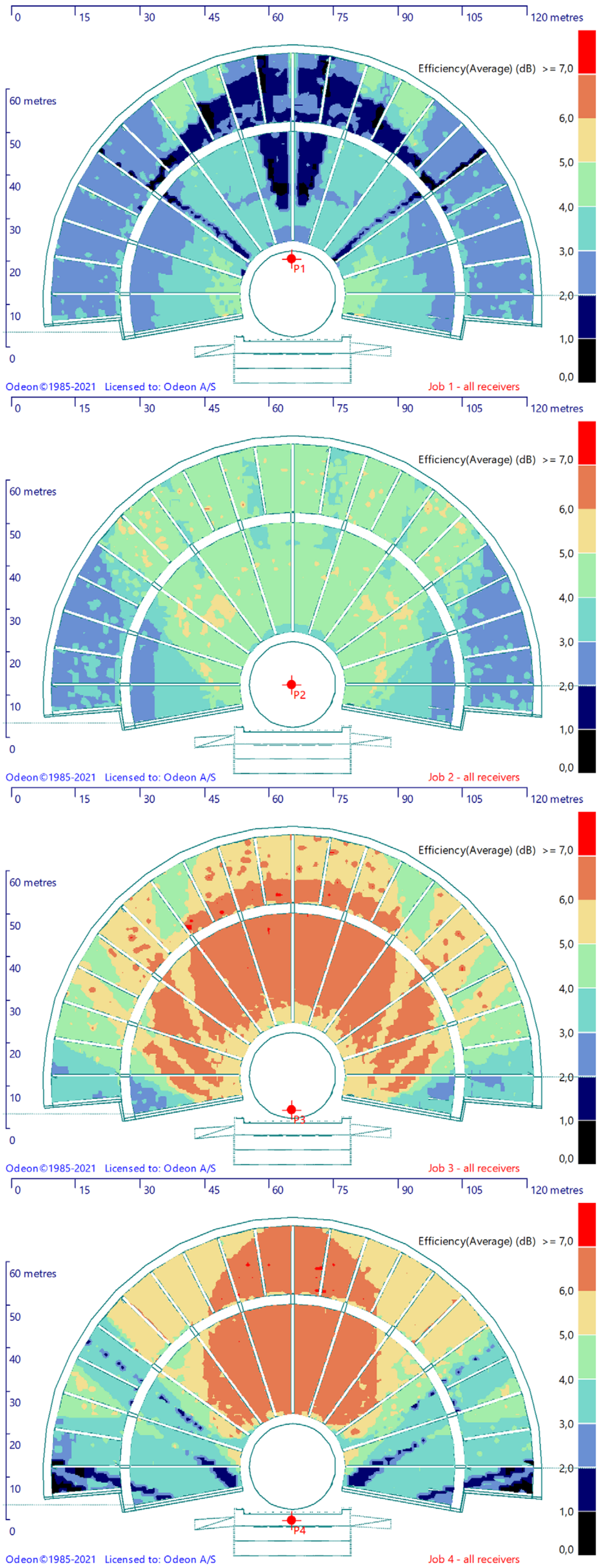

Figure 8. Grid responses of efficiency E_m at mid frequencies, calculated with four different source positions.

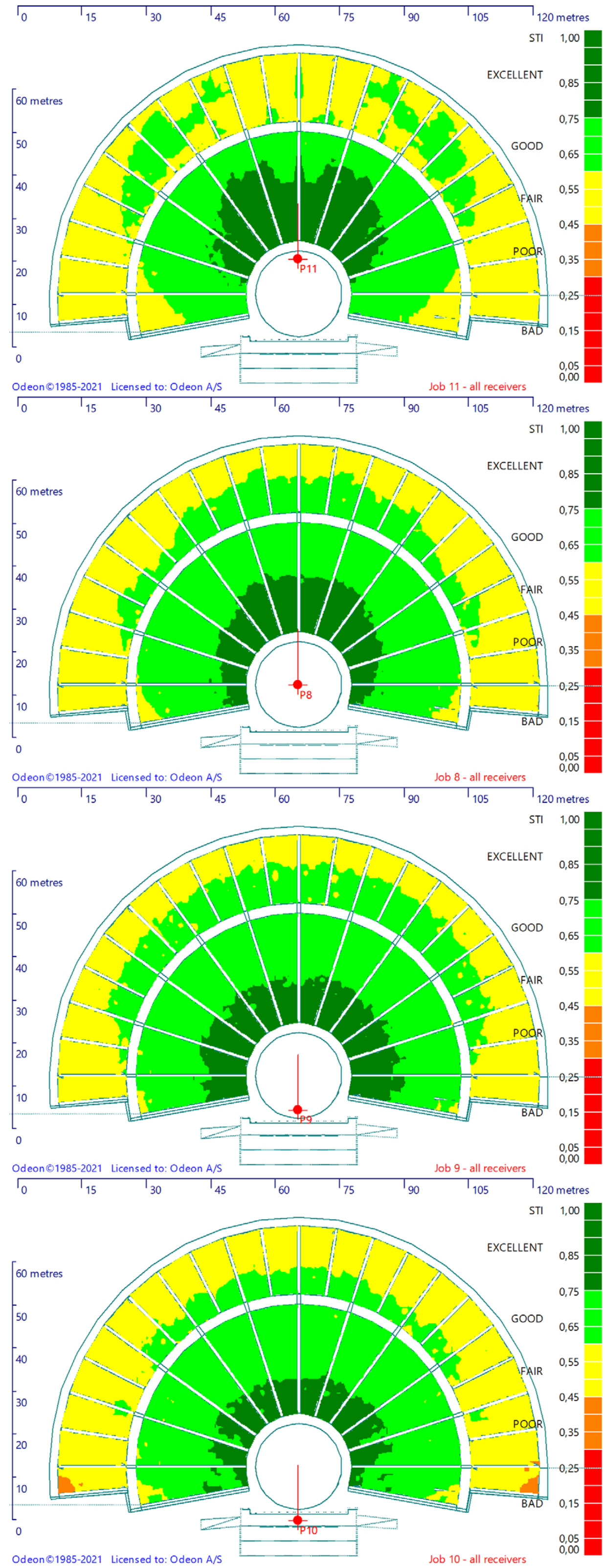

Figure 9. Grid responses of STI for loud speech, calculated with four different source positions.

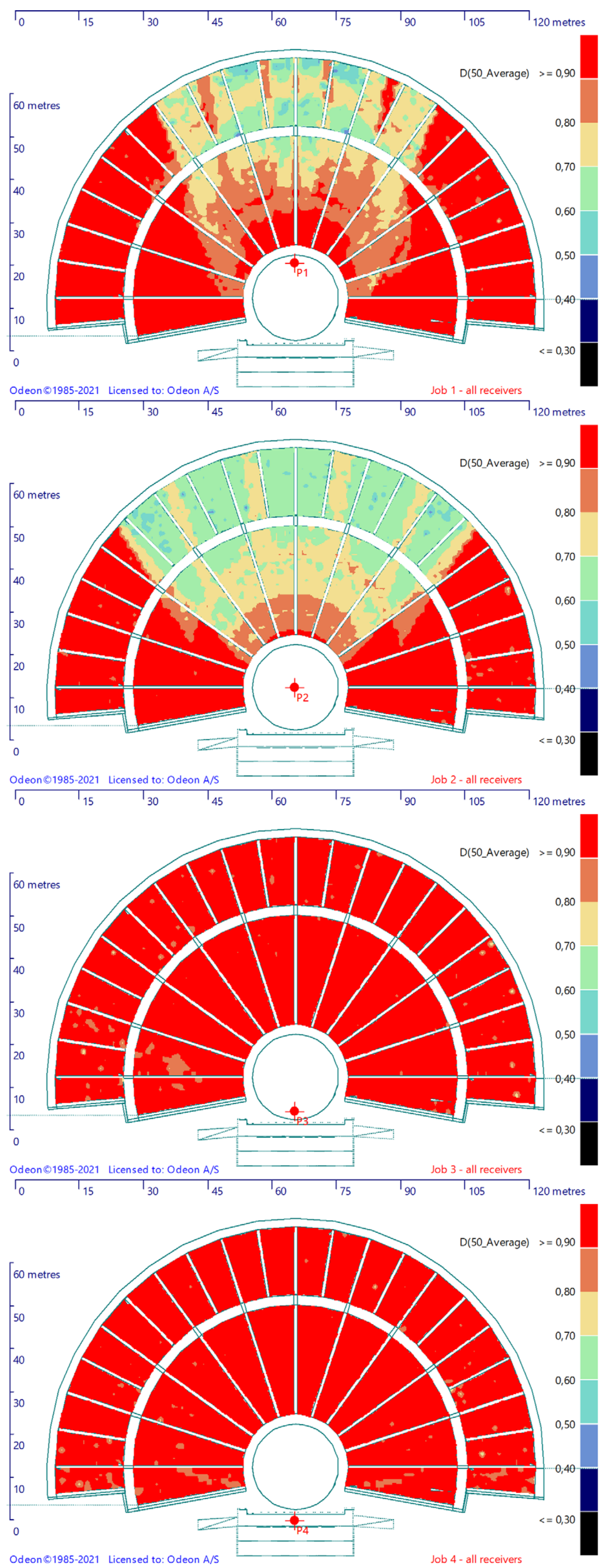

Figure 10. Grid responses of definition $D_{50,m}$ at mid frequencies, calculated with four different source positions.

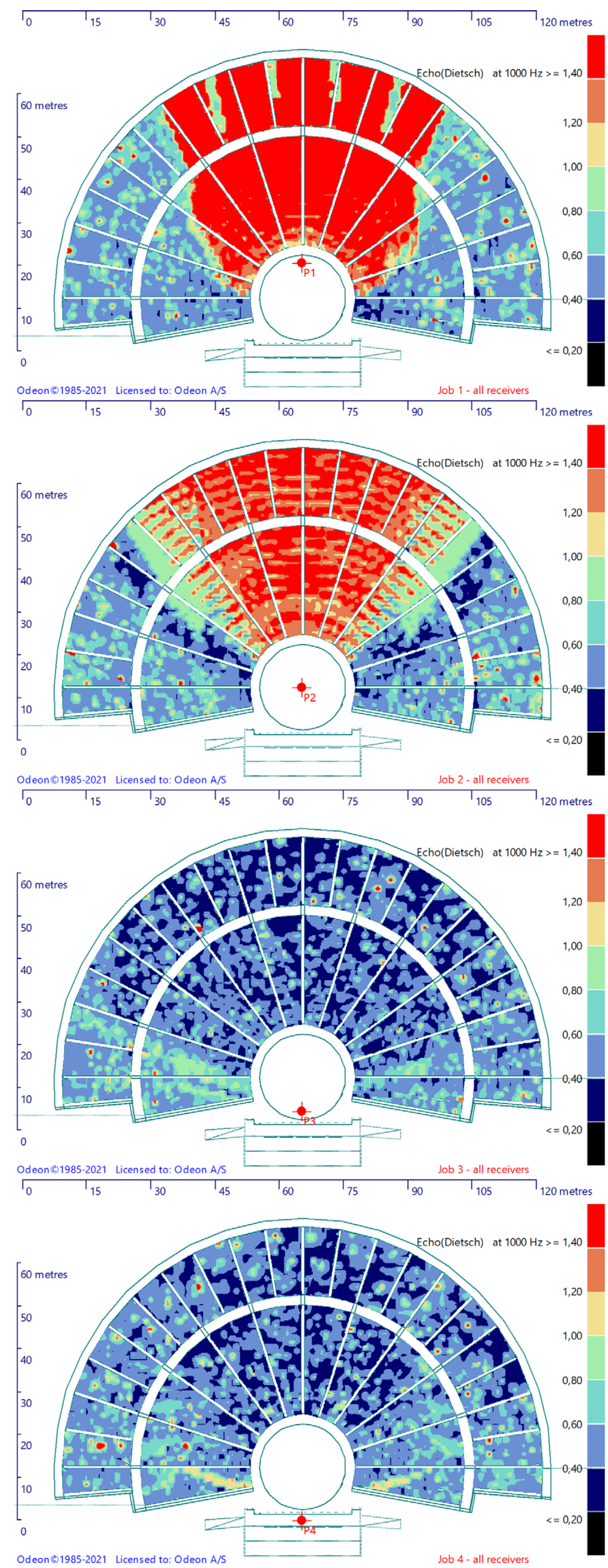

Figure 11. Grid responses of Dietsch echo criterion at 1 kHz, calculated with four different source positions.

higher efficiency and thus they are acoustically better than positions A and B. This is because the sound reflections from orchestra and scene building are contributing more efficiently to the sound level with source positions C and D.

The grid responses for acoustical parameters related to clarity of speech are shown in Figures 9–11. The STI of very loud speech from a source with directivity and spectrum as a human talker is shown in Figure 9. This can be compared with the results for the definition parameter $D_{50,m}$ using an omni directional sound source, shown in Figure 10. The most obvious difference between the results is seen, when source positions B and C are compared. While the STI results indicate equally good listening conditions for the two sources, the $D_{50,m}$ results indicate a substantial difference with lower clarity in the middle part of the audience from source position B. Figure 11 shows the Dietsch echo parameter. The echo problems that are related to source positions A and B are clearly seen. It is also seen that the definition $D_{50,m}$ gives lower values when there is an echo, but this is not the case for the STI. This example shows that the STI parameter must be used with great caution in open-air theatres and other scenarios where echoes can occur.

5 Conclusion

In an open-air theatre, the reflection density is sparce and the energy of late reflections can be very low. It is found that reverberation time and EDT are problematic and not meaningful in an open-air theatre.

The sound strength G and the definition D_{50} are found to be meaningful for characterizing the loudness and the clarity of speech, respectively, in an open-air theatre.

The risk of a disturbing echo is much higher than in a closed room. In order to identify possible echo problems, the echo parameter for speech by Dietsch and Kraak [21] is found to be very useful.

It is found that the STI is applicable with caution, but not reliable in an open-air theatre where echoes can occur.

A new parameter is suggested for the acoustical efficiency. This has a relatively small variation with position, and thus the spatial average efficiency is suggested as a global acoustical parameter that can be useful for comparison of different theatres or different stage conditions within a theatre.

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Cite this article as: Rindel JH. 2023. A note on meaningful acoustical parameters for open-air theatres. Acta Acustica, **7**, 20.