Meaningful acoustical parameters for open-air theatres

Jens Holger Rindel[1]

[1] Odeon A/S, Denmark, jhr@odeon.dk

ABSTRACT

The reverberation time and other acoustical parameters defined in ISO 3382-1 have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theatre. Low reflection density and lack of late reflections mean that the reverberation parameters are unreliable. It is necessary to re-think the need for acoustical parameters. The most important acoustical features of a theatre are that speech is sufficiently loud and clear. In addition, an echo-parameter is needed.

Keywords: acoustical parameters, speech, echo.

1. INTRODUCTION

The acoustics of performance spaces are usually characterised by the reverberation time and a handful of other acoustical parameters defined in ISO 3382-1 [1]. The reverberation time has normally little spatial variation within a room and thus the position-averaged reverberation time works well as a global descriptor of the acoustics. Other parameters like EDT, sound strength and clarity are useful to describe the variation over the audience area of acoustical conditions.

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 re-think 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 out-door environment where the reflection density is low. 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, see Vitruvius [2, 5.8.1-2].

2. 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. Thus, for the acoustical simulations, the vocal effort should be between ‘loud’ and ‘shouted’ as defined in ANSI 3.5 [3]. Suggested source data are the A-weighted 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 can be modelled with the data from Chu & Warnock [4].

As an example, acoustical calculations are made for the reconstructed Greek theatre in Thorikos. A speech source as described above is used and the acoustical parameters are total A-weighted SPL and the Speech Transmission Index (STI) [5], calculated both with and without the sound absorption of an audience, see Table 1.

Table 1 – Average and standard deviation of acoustical speech parameters calculated in Thorikos theatre with or without audience. Source positions are on orchestra in front (A) middle (B) or back (C). Ten receiver positions cover first to last row in the centre of the theatre.

Parameter	Source pos. A		Source pos. B		Source pos. C	
	Avg.	S.d.	Avg.	S.d.	Avg.	S.d.
SPL(A), audience	60,0	4,9	59,3	3,3	57,6	2,7
SPL(A), empty	61,2	5,2	60,0	3,6	58,7	3,1
STI, audience	0,80	0,08	0,81	0,06	0,79	0,04
STI, empty	0,77	0,08	0,77	0,05	0,75	0,03

For the STI calculations, the background noise was set to 35 dB A-weighted (pink noise). The spatially averaged STI values are 0,75 or higher, which corresponds to ‘excellent’ speech perception. However, the STI results can be misleading, because echo problems are not included, see the discussion below.

The spatially averaged A-weighted SPLs are around 60 dB, a little higher with source in position A (front) and a little below with source in position C. For comparison, the preferred median 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 [6].

3. PARAMETERS FOR MEASUREMENTS

Acoustical parameters suitable for measurements should preferably meet the principles in ISO 3382-1, 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.

3.1 Impulse response

Again, the reconstructed Greek theatre in Thorikos is used as an example. The squared impulse response shown in Figure 1 is from source position B in the centre of the orchestra with a receiver on the last row. It is characteristic 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.

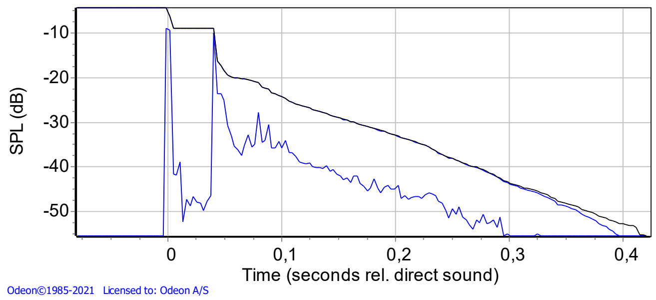

Figure 1 – Simulated squared impulse response (blue) and the integrated Schroeder curve (black) at 1 kHz octave band. This is from a reconstruction of the Thorikos theatre without audience, source position B in centre of the orchestra and receiver in the middle of last row.

Figure 1 also shows the integrated squared impulse response. This curve is very irregular over the initial 15 dB, due to the time delay gap. 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). Other reverberation time parameters like T_{20} are also highly problematic, because the start of the evaluation range (5 dB below the maximum) is not well defined. 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? During a performance, the late reverberation is not audible.

Results of several acoustical parameters derived from the impulse responses are shown in Table 2. Average and standard deviation are shown using ten receiver positions and three source positions. The echo parameter is from Dietsch & Kraak [7]. The efficiency E is defined below.

Table 2 – Average and standard deviation of acoustical parameters calculated in Thorikos theatre without audience. Source and receiver positions are as in Table 1. All results are for the 1 kHz octave band.

Parameter	Source pos. A		Source pos. B		Source pos. C	
	Avg.	S.d.	Avg.	S.d.	Avg.	S.d.
EDT (s)	0,88	0,33	0,57	0,13	0,36	0,25
T_{20} (s)	0,75	0,05	0,74	0,04	0,84	0,13
ξ (T_{20}) (‰)	28,0	8,8	17,6	9,7	29,0	19,9
T_S (ms)	24	7	23	2	22	4
G (dB)	1,4	5,0	0,6	3,5	-0,1	3,1
D_{50}	0,77	0,09	0,89	0,02	0,89	0,05
C_{50} (dB)	5,5	2,7	9,4	0,9	9,4	1,9
Echo - Dietsch	1,07	0,35	0,52	0,09	0,53	0,10
Efficiency E (dB)	2,8	0,7	4,9	0,4	6,3	0,4

3.2 Reverberation parameters

The EDT varies strongly over the positions, the standard deviation is high, see Table 2. This is as expected from the observation of the typical impulse response above. It is concluded that EDT is not a meaningful parameter for an open-air theatre. A similar observation was made by Farnetani et al. [8].

The spatial variation of the reverberation time T_{20} is more moderate. However, the ξ parameter gives a clear warning that something is wrong. This parameter is defined in annex B of ISO 3382-2 [9]. 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 2 indicate that this condition is strongly violated in nearly 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 & Wang [10].

3.3 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 distance of 10 m. It is defined in [1, eq. (A.1)]:

$$G = L_p - L_{p,10} \quad \text{dB} \qquad (1)$$

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 5 dB with source position A and around 3 dB with source positions B and C. The great 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 [8, 10, 11].

3.4 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, Annex A]. In addition, it is mentioned in a note [1, Annex A] 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. 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. The two parameters are related by the equation:

$$C_{50} = 10 \lg\left(\frac{D_{50}}{1 - D_{50}}\right) \quad \text{dB} \qquad (2)$$

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 dB-levels (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 has the advantage of no sharp time limit, but it is rarely used.

The 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. The parameter is intended for electroacoustic communication systems, not for room acoustics. Never the less 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 serious problems with the STI, especially when applied to a situation with low reflection density. Onaga et al. [12] have shown that STI responds to single reflections in the same way whether the time delay 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 & Nagy [13]. 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 3. Best correlation is for the D_{50} parameter (mid frequency average of 500 Hz and 1000 Hz octave bands). Thus, if for example D_{50} exceeds 0,55, it can be assumed with high certainty that STI will be in the range 'Good'. Similarly, the range 'Excellent' can be assumed when D_{50} exceeds 0,80 or C_{50} exceeds 8 dB.

Table 3 – Relationship between speech clarity parameters (mid frequencies) and the STI (average minus standard deviation) derived from measured data in rooms, Fürjes & Nagy [13].

	Quality:	Poor	Fair	Good	Excellent
Parameter	R^2	STI ≥ 0,30	STI ≥ 0,45	STI ≥ 0,60	STI ≥ 0,75
D_{50}	0,93	≥ 0,05	≥ 0,30	≥ 0,55	≥ 0,80
C_{50} (dB)	0,89	≥ -13	≥ -6	≥ 1	≥ 8
T_S (ms)	0,85	≤ 550	≤ 230	≤ 95	≤ 40

3.5 Acoustical efficiency

The efficiency E in dB is defined as the amplification of the sound provided by the theatre, calculated as the total SPL minus the SPL of the direct sound alone. 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 0 dB and 9 dB.

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:

$$E = L_p - L_{p,d} = G - 20\lg\left(\frac{d}{10}\right) \quad \text{dB} \qquad (3)$$

where d is the distance in metres from source to receiver. 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 amplify the sound from a given position.

A similar approach was suggested by Farnetani et al. [8], 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).

4. DISCUSSION

Figure 2 shows examples of calculated grid maps of some acoustical parameters in the reconstructed Thorikos Greek theatre and the well-preserved Aspendos Roman theatre. The architecture of the Roman theatre gives rise to a higher reflection density and more late reflections than found in the Greek theatre, but still some echo problems are noted.

As expected, the efficiency E is less dependent on distance from the source than G. Comparison of the results for the echo parameter with the STI results confirms the fact, that STI is unreliable in cases with echo problems. The D_{50} results are quite similar to the STI results, but the D_{50} behaves much better than STI in cases with echo problems.

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 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 suggested by Dietsch & Kraak [7] is found to be very useful.

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.

6. REFERENCES

[1] ISO 3382-1. *Acoustics – Measurement of room acoustic parameters - Part 1: Performance spaces*. Geneva, 2009.
[2] M. Vitruvius Pollio. *Ten Books on Architecture* (English translation, Ingrid D. Rowland and T.N. Howe). Cambridge University Press, 2001.
[3] ANSI 3.5. *Methods for Calculation of the Speech Intelligibility Index*. American National Standards Institute, Inc. 1997.
[4] W.T. Chu, A.C.C. Warnock. *Detailed Directivity of Sound Fields Around Human Talkers*, IRC-RR 104, National Research Council, Canada, 2002.
[5] IEC 60268-16. *Sound system equipment – Part 16: Objective rating of speech intelligibility by speech transmission index*. Geneva, 2011.
[6] E. van Heusden, R. Plomp, L.C.W. Pols. Effect of ambient noise on the vocal output and the preferred listening level of conversational speech. *Applied Acoustics* 12, 31-43, 1979.
[7] L. Dietsch, W. Kraak. Ein objektives Kriterium zur Erfassung von Echostörungen bei Musik- und Sprachdarbietungen. *Acustica,* 60, 205-216, 1986.
[8] A. Farnetani, N. Prodi, R. Pompoli. On the acoustics of ancient Greek and Roman theaters. *J. Acoust. Soc. Am.* 124, 1557-1567, 2008.
[9] ISO 3382-2. *Acoustics – Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms*. Geneva, 2008.
[10] F. Mo, J. Wang. Why the conventional RT is not applicable for testing the acoustical quality of unroofed theatres. *J. Acoust. Soc. Am.* 131, 3492, 2012.
[11] E. Bo, L. Shtrepi, F. Aletta, G.E. Puglisi, A. Astolfi. Geometrical acoustic simulation of open-air ancient theatres: Investigation on the appropriate objective parameters for improved accuracy. *16th IBPSA Conference*, 2-4 September, Rome, 2019.
[12] H. Onaga, Y. Furue, T. Ikeda. The disagreement between speech transmission index (STI) and speech intelligibility. *Acoust. Sci. & Tech.* 22, 4, 265-271, 2001.
[13] A.T. Fürjes, A.B. Nagy. Tales of more than One Thousand and One Measurements (STI vs. room acoustic parameters -a study on extensive measurement data) Preprint · May 2020 DOI: 10.13140/RG.2.2.15781.0176.

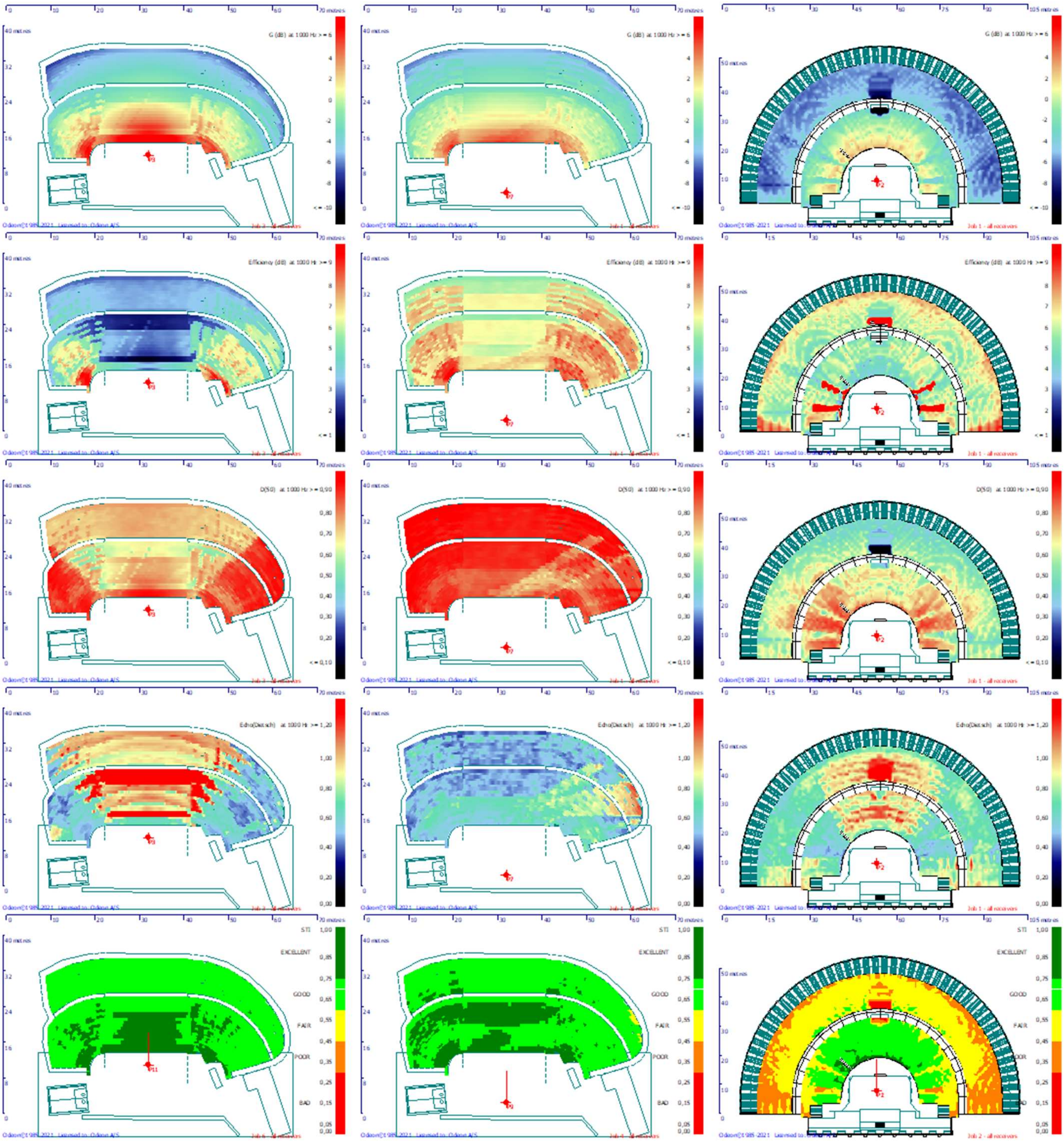

Figure 2 – Grid responses of calculated acoustical parameters from top to bottom: G, E, D_{50}, Echo (Dietsch), and STI (directional source). Left: Thorikos theatre with source position in front on orchestra. Middle: Thorikos Greek theatre with source position in back on orchestra. Right: Aspendos Roman theatre with source on a modern scene.