



PROJECT ANCIENT ACOUSTICS PART 1 OF 4: A METHOD FOR ACCURATE IMPULSE RESPONSE MEASUREMENTS IN LARGE OPEN AIR THEATRES

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Selecting an appropriate method for measuring ‘normal’ indoor concert hall acoustics is always a trade-off between time, stimulus type, number of measurements and measurement quality. For ISO 3382 room acoustic parameters to be derived accurately from impulse responses, this trade-off aims at a certain minimum decay range. Previously, there have been many attempts to obtain room acoustical parameter values in ancient amphitheatres, using hand claps, balloons, fire crackers, blank pistols, deterministic signals played by loudspeaker sound sources, etcetera. However, results are presented mostly without describing or discussing the quality of the obtained impulse responses (IR’s). Part of the Ancient Acoustics research project was to find out how to accurately measure many open air impulse responses in accordance with the ISO 3382 standard, under restricted time and resource conditions. Practical ‘measurement training’ in a Dutch open air amphitheatre resulted in a measurement setup and procedure that would meet the predefined requirements for measuring ancient amphitheatres. To reduce measuring time, asynchronous measurements (without cables) were carried out using multiple microphones and recording devices, as well as multiple dodecahedron sound sources playing the stimulus signals simultaneously. In addition, speech intelligibility measurements were performed using a separate speech source. This finally led to more than 10,000 accurate impulse responses for three theatres. This part of the study will focus on the method used to perform such a large number of good quality measurements within a day per amphitheatre. We will discuss the effect of device clock speed mismatch due to signal asynchronicity, sound source directivity errors, system variance by meteorological influences and the effect of background noise on the impulse response decay range, using the Impulse response to Noise Ratio (INR) and the Just Noticeable Difference (JND) as quality measures.

1. Introduction

To confirm or disclaim the exceptional acoustical quality of Greek amphitheatres or to verify computer models in order to predict architectural reconstructions in the future, many measurements have been conducted to investigate the ‘acoustics’ of ancient amphitheatres [1-5]. In these studies most of the room acoustic parameters are derived from impulse response (IR) measurements, mostly presented without describing or discussing the reliability/quality of these impulse responses in terms of impulse response decay range. If used, the decay range is not always well defined. The ‘Ancient Acoustics research project’ [6] consists of a set of 4 coherent studies: Part 1 (this part): ‘Measurement method’; Part 2: ‘Measurement data’ [7]; Part 3: ‘Ray based modelling’ [8]; Part 4: ‘Stage acoustics’ [9]. In this study (part 1) the aim was to find out how to accurately measure many open air IR’s in accordance with the ISO 3382 and IEC 60268-16 standards [10,11], under restricted time and resource conditions, reaching a minimum IR decay range (INR) of 35 dB for the room acoustic parameters and 25 dB for the speech parameters, resulting in an accuracy of 1 JND for all measured parameters in this project [7]. In preparation for the measurement expedition,

acoustic outdoor measurements were conducted on a lawn in a (noisy) urban environment. Line measurements were carried out over approx. 90 m, the longest source-receiver (SR) distance in this study (theatre of Argos). The goal (the main challenge) of this preliminary study was to find out how to do qualitatively reliable measurements over large source-receiver distances, in spite of a lot of background noise and other negative environmental effects (such as wind) using an asynchronous measurement technique. The ‘Kersouwe’ open air theatre in Heeswijk-Dinther (Netherlands), built in the mid 1940’s, was the first theatre where the measurement setup and script were tested. The ‘real’ measurements (four complete sessions) have been performed in March, 2016: the Odeon of Herodes Atticus on Thursday 24-03-2015 from 08:00 a.m. to 11:15 a.m. (daytime session) and from 06:30 p.m. to 09:30 p.m. (evening session); the theatre of Epidaurus on Friday 27-03-2015 from 08:00 a.m. to 08:00 p.m. and the theatre of Argos on Monday 30-03-2015 from 01:30 p.m. to 04:00 p.m. The day before the acoustic measurements the detailed geometry of the theatre was determined using an automated theodolite. Also some acoustic test measurements were carried out.

Section 2 of this paper contains a short description of the theatres both in terms of constructional shape and environmental conditions. Section 3 deals with the measurement setup and the measurements. Sections 4 and 5 present the results, the discussion and the conclusion.

2. Theatres and measurement conditions

2.1 Introduction

The three open air theatres under test were the Odeon of Herodes Atticus, the large theatre of Epidaurus and the theatre of Argos. These theatres differ highly in shape, dimensions, architectural and structural condition. Also the locations and the prevalent background noise are quite different. A global impression of the theatre dimensions and schematic top views are presented in Fig. 1.

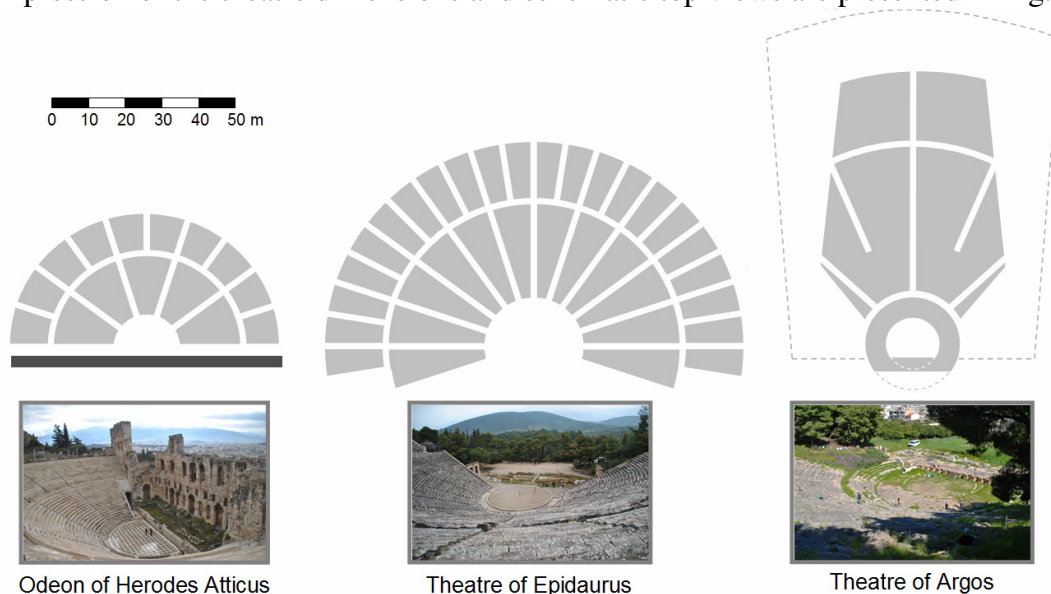


Figure 1: Impressions and schematic top views of the open air theatres under test. The white lines are corridors. The horizontal dark grey line in the left view is an acoustically reflective wall. The dashed line in the right view is the (rough) ancient contour.

2.2 Short description of the open air theatres and outdoor climate conditions

The Odeon of Herodes Atticus (hereafter also denoted by ‘Odeon H.A.’) is located on the slope of the Acropolis in the urban environment of Athens and is not accessible to tourists. It provides well restored seating for approx. 5,000 people (summer concerts). A striking difference between this theatre and the other two is the sound reflective stage back wall (scaenae frons). Because of its urban location there was a high level of continuous background noise during day time caused by traffic, machinery and music making people, reaching an average background level of 47 dB(A) and

predominantly music making people in the evening reaching a level of 41 dB(A). The average air temperature and relative humidity during the measurements were 17 ± 2 °C and 60 ± 9 % respectively in the morning, and 15 ± 1 °C and 70 ± 1 % in the evening. During the measurements the average wind speed varied between 0.5 and 1.5 m/s during both morning and evening.

The (large) theatre of Epidaurus (hereafter also denoted by ‘Epidaurus’) is located on the slope of the mount Kynortio in a natural environment. It provides seating for approx. 14,000 people (ancient drama performances during summertime). Beside the larger dimensions and the more than 180 degree shape of the audience area, a missing scaenae frons (large wall behind the stage) and a missing proscaenium (stage border) are the important (architectural) differences between this theatre and Odeon H.A. During the measurements there were lots of moments with raised background noise levels caused by animals (stray dogs, birds, and crickets). By choosing the right measurement moments, without tourist groups (singing and ‘experimenting’) the average background noise level L_A during the measurements was just 35 dB(A). The average air temperature was 14 ± 3 °C. The average relative humidity while doing the measurements was 86 ± 5 %. The wind speed varied between 1 and 1.5 m/s.

The theatre of Argos (hereafter also denoted by ‘Argos’) was one of the largest theatres in Greece. It is located in front of the city Argos on the slope of the castle (“Larissa”) hill. In its original state it provided seating for approx. 20,000 people. The shape of this theatre differs a lot from the ‘traditional fan shaped’ theatres like Odeon AH and Epidaurus. In its current state the theatre of Argos does have a proscaenium but no scaenae frons. The proscaenium has the effect that the lower seats of the theatre are clearly audibly shielded from the city noise of Argos. The higher the seats the more interference during the measurements, but also the more they are degraded (crumbled) and overgrown by vegetation. These higher seats are no longer usable for audience. Measurements were performed in the afternoon. During the measurements the average background noise level L_A was 41 dB(A), the average air temperature was 22 ± 1 °C and the average relative humidity was 35 ± 2 %. The average wind speed varied between 0.5 and 1.7 m/s with an increase of gustiness (max 4 m/s) as the day progressed. No measurements were carried out during wind speeds higher than 2.5 m/s to avoid small movements of the microphones.

2.3 Measurement positions

The IR measurements were performed on equally distributed radial lines using 20 omnidirectional microphones ($h = 0.8$ m above seating place) on one line and 2 omnidirectional sound sources ($h = 1.5$ m): one in the centre and one out of the centre of the orchestra. The number of lines depended on shape and dimension of the theatre resulted in 400, 528 and 120 source-receiver combinations for respectively Odeon H.A., Epidaurus and Argos. Besides, directional transducers were used: a (directional) speech source and a head and torso simulator (HATS). The speech intelligibility measurements were carried out with the speech source at the centre of the orchestra, pointing into the direction of the centre line (axis of symmetry). The HATS was used for both room acoustic and speech intelligibility measurements. More than 10,000 measurements were performed. For detailed information about sound source and microphone positions please refer to part two and four of this series of papers “Project Ancient Acoustics” [7,9].

3. Measurement method and accuracy

3.1 Measurement method

To minimize the effective measurement time, the measurement set consisted of 2 omnidirectional (dodecahedron) sound sources, one for each source position and 20 microphones placed on a straight line from the front row to the back row of the theatre. During the measurements both sound sources were simultaneously generating the same measurement signal thereby not ‘affecting’ each other. After each ‘line-recording’ the microphones were moved to the next measurement line. The IR’s were obtained by afterwards deconvolving the recorded signal with the measurement (input) signal.

3.1.1 Asynchronous measurement

Impulse response measurements based on deconvolution techniques normally require a connection between the stimulus generator and the response recording device. This is inconvenient for long distance measurements and when using many microphones. Playing the excitation signal from an arbitrary playback device generally introduces errors due to a clock speed mismatch between the signal player and the response recorder. Details about the effect of clock speed errors caused by asynchronous measurements related to the used measurement devices for this study are described in Section 3.2.

3.1.2 Measurement equipment

The measurements were carried out asynchronously using 2 omnidirectional sound sources and 10 (two-channel) digital sound recorders, one for each two measurement positions. The final result was a recording for every receiver position of a set of 2 overlapping sweeps, where each separate source produced one sweep. Fig. 2L shows the setup with all its components (device name, manufacturer, type code etc.) for the 2-channel asynchronous measurement.

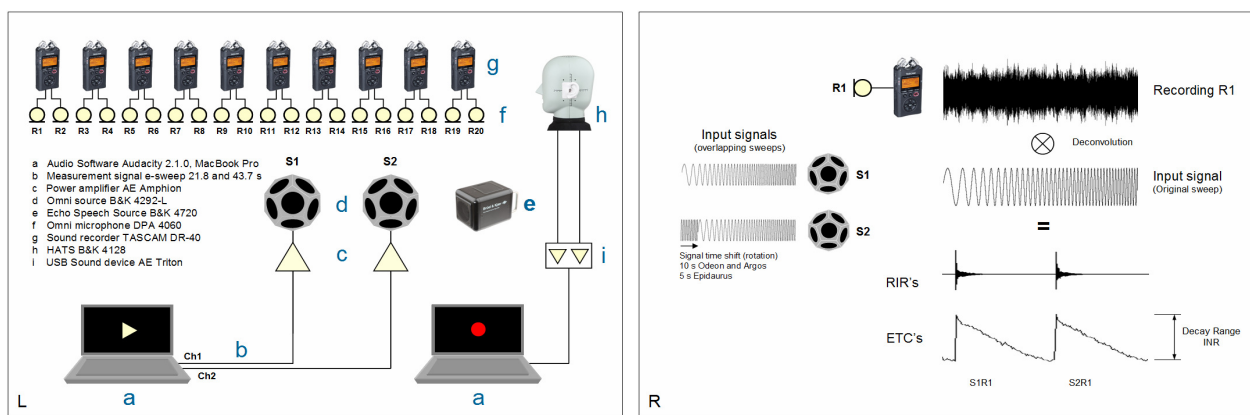


Figure 2: Left (L) Setup for the 2-channel asynchronous impulse response measurements. Right (R) Signal analysis for one digital sound recorder. Deconvolution of the recorded signal with the original e-sweep results in a response train. Each IR or its derived Energy Time Curve (ETC) represents one sound source position.

In addition to two omnidirectional sound sources and omnidirectional microphones, a level calibrated speech source in accordance with the IEC standard 60268-16 and a HATS were used. These devices are also shown in the setup presented in Fig. 2L. The octave band sound power spectrum of both sound sources (omni and speech) used for all measurements in this study is given in section 3.3 and presented in Fig. 3.

3.1.3 Measurement signal and analysis

Using exponential sweeps as measurement signals and the deconvolution technique makes it possible to overlap measurement signals when using multiple sound sources. This technique has been proven in an earlier experiment using 8 omnidirectional sound sources [12] and can save a lot of measuring time, particularly in this case using relatively long measurement signals. For a theoretical decay range of 60 dB the delay or rotation shift should at least equal the reverberation time. Previous measurements [1,3,5] show that the longest reverberation time in an empty open air theatre never exceeds a value of 3 s. Long distance measurement experiments in the preliminary study under different wind and noise conditions brought out two measurement signals. One with a length of 43.7 s and a rotation shift of 10 s (Odeon H.A and Argos) and one with a length of 21.8 with a rotation shift of 5 s (Epidaurus). The used speech source generates a fixed MLS based signal with a length of 10.9 s. The length of all signals is based on a multiple of $2^n/48k$ as used in the DIRAC software. To improve the decay range for the speech measurements using the speech source, a pre-average value of 10, 11 and 16 was used for Odeon H.A., Epidaurus and Argos respectively.

3.2 Device clock speed mismatch

Playback and recording speed errors are usually caused by sample rate deviations. The stimulus speed error is the deviation of the stimulus playback device sample rate relative to the deviation of the response recorder sample rate. Therefore, in case of opposite signs, the speed errors of these devices magnify each other. In case of equal signs, the errors partly compensate each other. In a previous study we have shown which speed differences are to be expected and how common room acoustic parameters will be affected [13]. Using an e-sweep as a measurement signal, maximum clock speed errors of 1000 ppm are allowable to measure all standard room acoustic parameters within an accuracy below 0.5 JND. Using MLS as a measurement signal (in this study generated by the speech source) clock speed differences of even less than 20 ppm can be unusable. The maximum clock speed error for all used combinations of sound devices in this study is 75 ppm: small enough for e-sweep deconvolutions, but too high for MLS signals. To remove any clock speed error between transmitter (input signal sound source) and receiver (digital recorder), time stretching by resampling was used prior to deconvolving the recordings by Dirac. For all devices the nominal sample frequency was set to 48 kHz and sync pulses were recorded for convenience in the processing.

3.3 Sound power level, background noise and system variance

IR measurements using deconvolution are sensitive to system variance caused by wind velocity (gusts), temperature changes, movements of people and transducers. Under normal conditions this results in a frequency dependent reduction of the decay range (derived from the Energy Time Curve ETC). It should be noted that the sensitivity for MLS signals is much greater than for sweep signals, comparable with the clock speed error differences mentioned in section 3.2. Fast variances within the measurement time have more impact on the IR quality than slow changes. The negative influence of time variance can be reduced by the correct choice of measurement signal and measurement time. The influence of background noise can be reduced by increasing the sound power levels until signal distortion becomes significant. Fig. 3 shows the background noise levels during the measurements, derived from the level calibrated sound recordings and the sound power levels of both the omni and speech source used in this study.

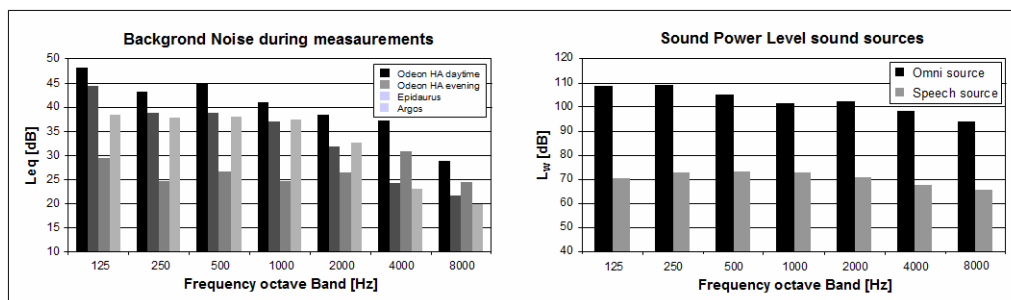


Figure 3: Left: background noise levels during the measurements derived from the calibrated recordings and right: sound power levels from omni source and speech source.

3.4 Sound source directivity

In previous research [14] it was found that the maximum directivity deviation from average within the critical distance of a dodecahedron sound source for frequencies higher than 500 Hz is ± 2 dB. When using 5 equal-angular positions, the maximum directivity deviation is reduced to ± 0.5 dB at all distances. In this study all omnidirectional sound source (dodecahedron) measurement results are presented as an average of 5 equal angular (rotation) steps.

4. Results and Discussion

4.1 Signal to noise ratio (SNR)

The signal to noise ratio at a certain measurement position is defined as the difference between the sound source level at that position and the background noise level caused by for instance environmental/urban activities, animals, people (tourists) and wind. Microphone windscreens were used to minimize the wind noise. Fig. 4 shows the equal distance averaged SNR values over all (radial) measurement lines for all theatres (Odeon H.A, Epidaurus and Argos) as a function of SR distance for both the omni source S1 and the speech source.

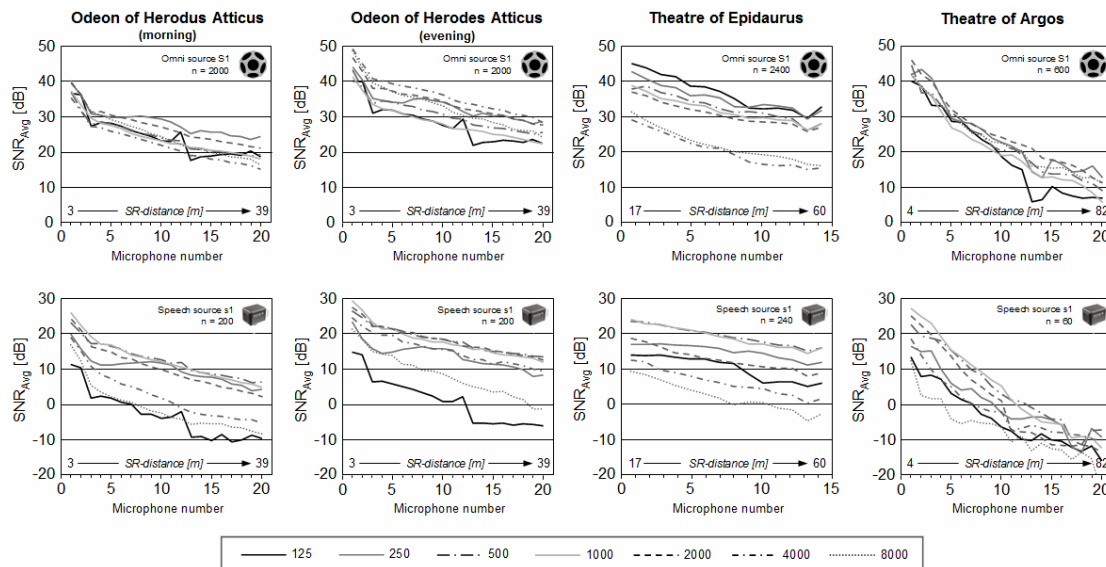


Figure 4: Equal distance averaged SNR values over all (radial) measurement lines for all theatres as a function of source receiver distance for both the omni source S1 and the speech source (S1).

As expected, starting at an SNR value of approx. 40 dB, in all cases for every octave band the SNR decreases gradually with the distance from the sound sources. In contrast to the (open) theatre of Argos, the SNR measured in the (open) theatre of Epidaurus reaches a more or less constant SNR value both for the omni source and the speech source at a distance of approx. 40 m. In Epidaurus the octave band values of 4000 and 8000 Hz are strongly affected by natural sounds caused by birds reacting to the sweep signals, resulting in 10 dB lower SNR values for both bands. In contrast to all other theatres, the SNR value in the lowest frequency band (125 Hz) measured in Epidaurus is significantly higher because of the absence of urban noise. Differences between day and evening in background levels caused by machinery, traffic and musicians result in SNR differences of approx. 5 dB.

4.2 Impulse response quality (INR)

Using deconvolution techniques, a low SNR value can be 'compensated' by increasing the measuring time. After deconvolution the end result was a set of 5,760 IR's obtained from the recordings in the Odeon of Herodes Atticus, a set of 3,168 IR's measured in the theatre of Epidaurus and a set of 1,226 IR's measured in the theatre of Argos. The quality of an IR is indicated by its decay range and can be represented using the INR (Impulse Response to Noise Ratio) expressed in dB [15]. All ISO 3382 room acoustic parameters derived from IR's require a certain minimum decay range (INR) to reach a certain accuracy. Fig. 5 shows the percentage of the measured IR's that exceed a certain decay range (INR) for both the omni source and the speech source. Beside the SNR, system variance caused by wind, temperature changes and movements of people and transducers affect the decay range (INR) of the measured IR. Another possible reduction in decay range can be caused by source receiver asynchronicity. The used measurement method and system should

aim at minimizing the impact of these factors. Results presented in the SNR and INR graphs (Fig. 4 and 5) lead to the dominant (impact) factor of background noise on the the decay range. Table 1 shows an overview of all obtained decay range values both for the omni and the speech source. This applies to every individual full octave band within the given range.

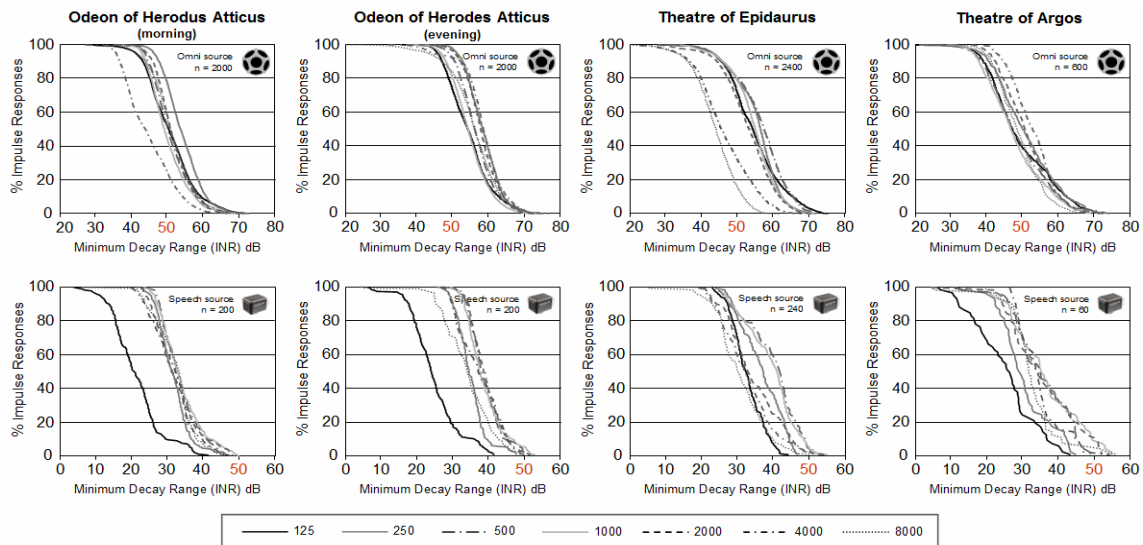


Figure 5: Percentage of the measured impulse responses that exceed a certain decay range (INR), for each theatre, for both the omni source S1 and the speech source, and in full octave bands from 125 to 8000 Hz.

Table 1: Percentage of the measured impulse responses that exceeds a certain decay range (INR)

Theatre	Omnidirectional sound source						Speech source		
	INR >25 dB	INR >35 dB		INR >45 dB			INR >25 dB		
	125-4k	125-4k	500-1k*	125-2k	250-4k	500-1k*	125-8k	250-8k	500-2k**
Odeon of Herodes Atticus morning	100%	97%	100%	81%	45%	83%	25%	82%	91%
Odeon of Herodes Atticus evening	100%	100%	100%	97%	95%	98%	43%	92%	100%
Theatre of Epidaurus	100%	93%	100%	88%	52%	91%	83%	83%	90%
Theatre of Argos	100%	96%	96%	56%	56%	56%	55%	78%	85%

*single number octave bands in accordance with ISO 3382-1 **RASTI octave bands in accordance with IEC 60268-16

4.3 HATS recordings

In addition to the one channel omni measurements in every theatre, (binaural) HATS recordings were also performed: 200 in Odeon H.A., 120 in Epidaurus and 30 in Argos, in order to get an idea of the IACC (Inter Aural Cross Correlation) in open air theatres and for auralization experiments. The quality of the binaural IR's is in line with the omni microphone measurements. 99% of all HATS IR's exceed the decay range value (INR) of 30 dB. To reach for example a minimum IACC accuracy of 0.5 JND (Just Noticeable Difference) a minimum INR of 25 dB is required [15].

5. Conclusion

Despite of restricted time and resource conditions, the used asynchronous measurement technique and simultaneously generated measurement signals resulted in more than 10,000 accurate impulse responses for 3 open air theatres in less than 3 days, preparation and geometrical inventarisation/measurement included. Assuming a desired minimum accuracy of 1 JND for all ISO 3382 parameters (with T_{20} as reverberation time parameter), using a standard dodecahedron sound source (generating an e-sweep), more than 95% of all measured IR's meet the requirements. Assuming a desired minimum accuracy of 1 JND for all IEC 60268-16 speech parameters, using a small single driver speech source (generating an MLS-signal), more than 85% of all measured IR's, meet the requirements. Compared with daytime measurements, evening measurements can lead to more than

5 dB higher decay ranges using the same equipment and settings. Evening measurements could be a recommendation to reach a 100% score.

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