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ACOUSTIC AND ENVIRONMENTAL PARAMETERS MEASUREMENTS IN EPIDAURUS ANCIENT THEATRE

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Abstract

Trying to understand more deeply the local influence of environmental factors and how they affect the spread of airborne sound by the constantly changing meteorological parameters and the refraction phenomena that occur based on: air temperature, relative humidity, wind velocity and wind direction, at different elevation points (comparison of tier close to ground level to top level tier), three portable weather stations were installed for a period of 55 hours at three different elevation points of the theatre for data logging and further processing. A thermal camera was also used to capture colour renderings of the cavea and orchestra surfaces.

At specific time periods during the day, measurements of objective acoustic parameters were performed such as Clarity C_{80}, Definition D_{50}, STI, RASTI, G Strength and others, using a sound source positioned at the centre of the orchestra area and three portable sound level meters as sound receivers. In addition, a dummy head with a set of binaural microphones was employed for measuring the IACC parameter, as well.

The measurements took place in two phases: Phase A (15-17.6.2011) measurements were performed under unstable weather conditions and quite low temperatures for summer season at the unoccupied theatre. Phase B (22-23.7.2011) measurement session was planned to be performed before a theatrical drama performance of Medea, also scheduled for that day, in order to reveal for the first time, through innovative scientific data, the objective acoustical characterisation of the theatre under different states of occupancy.

The results of the acoustic and meteorological measurements were compared and are presented in charts and graphs.

Keywords

Acoustic measurements
Audience absorption
Occupied/unoccupied
Environmental/meteorological measurements
Refraction of sound

1. Introduction

The acoustic and meteorological measurements of the present study took place in two phases:

Phase A: At 15th, 16th and 17th of June 2011 under unstable weather conditions and quite low temperatures for summer season, with large meteorological changes (in 24h period): dense cloud cover, time of intense rainfall, full sunlight period. The acoustic measurements were performed with dry ground surface (at orchestra area) except for a time period following a heavy rainfall (between 14.00-15.00 on 16.06.2011).

Phase B: At 22nd and 23rd of July 2011 under normal for season weather conditions (+10°C air temperature difference, in comparison with measurements made during the same hours-afternoon-in Phase A), with both absence and presence of audience. Occupied state measurements took place with attendance estimation ranging approximately from 300 to 3.500 people, 10 min before the theatrical drama performance of "Medea". The ground surface (at orchestra area) was exposed to water as usual scenery technique applied to the performances which also improves the acoustic reflection to the audience.

2. Methods

2.1 Instrumentation

The entity of measurements was performed by means of commercially available type-approved measurement instrumentation.

Acoustic Measurements

3 x Brüel & Kjær Hand-held Analyzer Type 2270-E incl. BZ-7225 Enhanced Logging software and BZ-7226 Sound Recording Option.
1 x Brüel & Kjær Hand-held Analyzer Type 2250-E incl. BZ-7225 Enhanced Logging software and BZ-7226 Sound Recording Option.
2 x Brüel & Kjær Type 4952 Outdoor microphone
2 x Brüel & Kjær UA-1404 Outdoor microphone kit
1 x Brüel & Kjær Type 4292 OmniPower Sound Source
1 x Brüel & Kjær Type 2716 Power Amplifier
1 x Brüel & Kjær Type 4100 Head and Torso Simulator
1 x Brüel & Kjær Type 4101 Binaural microphone
2 x Brüel & Kjær Type 4231 Sound calibrator
1 x Brüel & Kjær Type 7841 Dirac Room Acoustics software v.5
1 x MOTU Traveler 8ch I/O Firewire Audio Interface
1 x Notebook Windows 7

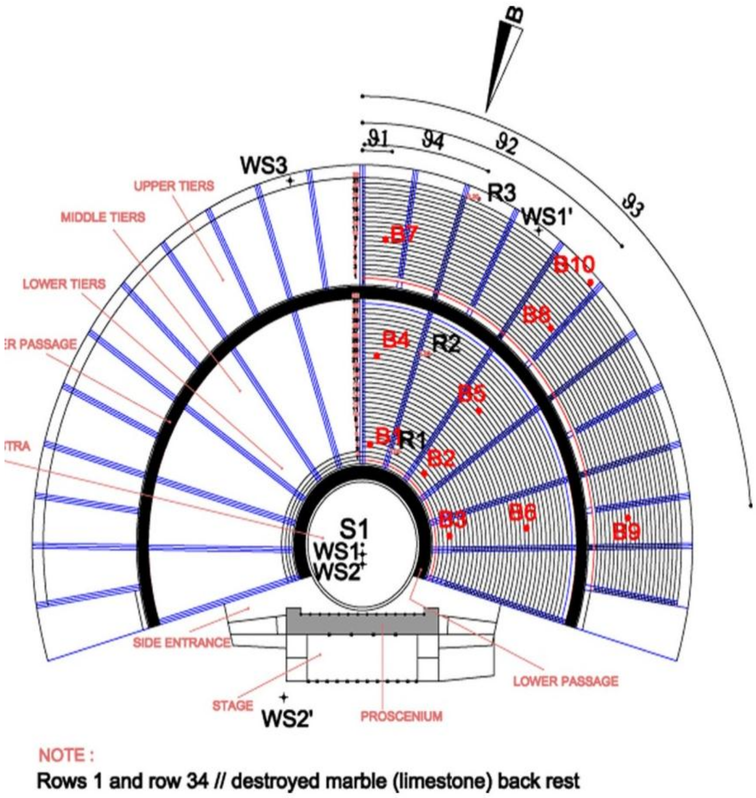
Meteorological Measurements	Distance Measurements	Accessories	Accredited Calibration
3 x Davis Vantage Vue Weather Station Sensor Suite 1 x Davis Envoy8x Data Logger 1 x Notebook Windows 7	2 x Leica Disto Laser Distance Meter	Brüel & Kjær Type 3535-A All-weather case, 1 x mast, 1 x <7m tripod, 4 x <1,5m tripod, extension audio and power cabling and others.	Brüel & Kjær Type 2250/70 Hand-held analyzers, Type 4952 Outdoor microphones and Type 4231 Sound calibrator employed, bear accredited calibration certifications.

Table 1 – Instrumentation

2.2 Acoustics Measurements method

2.2.1 Measurement Phase A (Theatre at an unoccupied state)

The acoustics measurement system consisted essentially of three portable B&K sound level meters as receivers R1, R2, R3, a B&K dummy head and binaural microphone set, for binaural measurements B1-10 and B&K dodecahedron loudspeaker as sound source S1 positioned at the centre of the orchestra (1,7m from the ground level) (fig.1). It should be noted that although in ancient times the main drama performance and speech took place at the proscenium, due to its absence nowadays and due to the specifications set by relevant past scientific work [1,2], it was decided to position the sound source at the centre of the orchestra area. Three portable sound level meters were employed as sound receivers. The stimulus signal generation (a. logarithmic sine sweep of 11 sec / 20 sec duration and b. pink noise in some particular tests at 105 dB-$L_{Aeq,10sec}$/1m, data acquisition, processing and derivation of acoustic parameters from the impulse response was performed using B&K Dirac software. The rest of the measurement signal chain consisted of outdoor microphones remotely connected to the sound level meters via factory approved audio signal extension cables to avoid signal degradation. The sound level meters were interfaced to the inputs of MOTU Traveler firewire audio interface featuring 'stepped' gain potentiometers in order to prevent level misadjustment of the finally calibrated measurement system.



	POSITION OF RECEIVERS	DISTANCE FROM S1 (m)
LOWER LEVEL TIER	R1-Single Channel	15.63
MIDDLE LEVEL TIER	R2-Single Channel	31.75
UPPER LEVEL TIER	R3-Single Channel	57.60
ALL TIERS	B1-B10 Binaural/Amphiotik	B1, B2, B3 : 15.63 B4, B5, B6 : 29.42 B7, B28, B9 : 47.59 B10 : 57.60
ANGLE (approximately)	$\Theta1=5^0$ $\Theta2=45^0$ $\Theta3=85^0$ $\Theta4 = 21^0$	
S1	Sound Source (H: +1.70)	
WS 1 (15-17.07.11) WS 1' (22-23.07.11)	Weather Station 1, 1' (H: +2.00 m)	
WS 2 (15-17.07.11) WS 2' (22-23.07.11)	Weather Station 2 (H: +7.00 m) Weather Station 2' (H: +2.00 m)	
WS 3 (15-17.07.11)	Weather Station 3 (H: +2.00 m)	

Figure 1 – Theatre plan view/instrumentation positions

Before the beginning of the measurement session, an in-situ calibration procedure took place comprising three subsequent calibrations:

a. Calibration of the audio interface within Dirac software.
b. Absolute level calibration of the sound level meters with B&K sound calibrator.
c. Calibration of the signal for measuring the StrenGth. The sound level meters or their outdoor microphones (with extension audio cables in the measurement chain) were positioned at the same height and at a 1m distance from the dodecahedron at -

90, 0 and 90 degrees around its hemispherical x/y-axis (0 degrees = centre of the orchestra facing the cavea).

With regard to the three receiver positions R1-R3 the objective was to multiply measure - at selected time intervals - the acoustic parameters at 'fixed' locations of different distance and height. As for the binaural measurements, the spatial distribution of parameters was mainly of interest. Along with the scheduled measurements, several particular tests were performed on-the-fly, employing the 4th sound level meter, as well:

a. Logging measurements of ambient background noise.
b. Logging measurements of typical vocal sound source levels and spectra.
c. Measurement of the acoustic feedback at orchestra (focusing on the performer).
d. Logging measurement of a cavea 'walkthrough' from top to the orchestra, in order to measure freq. response difference at varying distance/height (fig.15).
e. Measurement of G at a z/y-axis hemisphere of ~15m radius along the direction of wind in order to investigate the local propagation of sound emitted from a sound source positioned at the orchestra (fig.14).

2.2.2 Measurement Phase B (Theatre at an occupied state of appr. 3.500 attendants)

Due to limitations regarding the deployment of measurement instrumentation and performance of the actual measurement just minutes before the national premiere of a theatrical performance of 'Medea', the measurement setup had to be minimized. As a result, the acoustic parameters were measured at three receiver locations (2 single channel and 1 binaural): R1, R2 and B4. Additionally, other two sound level meters were positioned at the middle upper tier and upper row in order to measure and log sound pressure levels. The limitation in accessing the orchestra before the performance did not allow the calibration of the system for the measurement of StrenGth and, in addition, the logarithmic sine sweep was reduced to half duration, from 20 to 11 seconds in order to reduce the annoyance inflicted to the audience.

2.2.3 Objective acoustic parameters measured

The acoustic parameters derived from the impulse response using Dirac [3,4,5] software and subsequently examined, were:

(1) L_{Aeq}, L_{AF} and L_N sound pressure level (1/3 OB frequency analysis and broadband).

(2) Centre Time (Ts), the time of the centre of gravity of the squared impulse response, also called "Schwerpunktzeit" (1/1 and 1/3 OB frequency analysis) [6].

(3) Strength (G) logarithmic ratio of the integrated sound power of the measured impulse response to that of the response measured at a distance of 10 m from the same sound source in a free field (1/1 OB frequency analysis) [6].

(4) Definition (D_{50}) early-to-total arriving sound energy ratio, also called "Deutlichkeit" (1/1 and 1/3 OB frequency analysis).

(5) Clarity (C_{80}) early-to-late arriving sound energy ratio (1/1 and 1/3 OB) [6,7,8].

(6) Reverberation Times T_{20} and T_{30} derived from the decay curve section between 5-25 dB and 5-35 dB respectively below the initial level (1/1 and 1/3 OB frequency analysis).

(7) Speech Transmission Index (STI) and the simplified versions of STI that cover fewer frequency bands and/or different modulation frequencies: Rapid Speech Transmission Index (RASTI), STI Male/Female, STI for public address systems (STIPA Male/Female) (1/1 OB frequency analysis) [9,10,11,12].

(8) Inter-Aural Cross Correlation Coefficient (IACC) using binaural technique to measure how left and right ear signals with respect to early reflections/reverberant sound/both (time interval defined at 50 and 80ms) (1/1 and 1/3 OB frequency analysis).

2.3 Meteorological Measurements method

Meteorological measurement system consists of three portable weather stations at positions WS1, WS2 and WS3 (fig.1) logging continuously one minute averages, max and min of the following parameters: air temperature, humidity, wind velocity and direction, placed at specific positions at different height (elevation points) for the time periods of: 15.06.2011 10:17:00 to 17.06.2011 17:28:00 (fig.2-5) and 22.07.2011 18:16:00 to 23.07.2011 19:07:00 (fig.6-8).

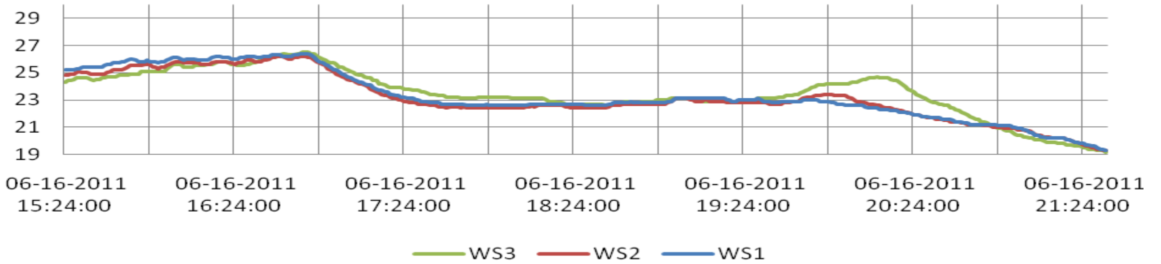


Figure 2 – Temperature °C/hour 16.06.2011

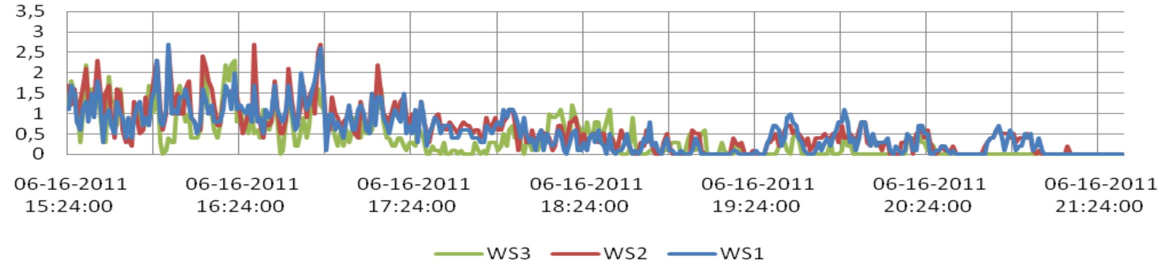


Figure 3 – Wind Speed Total 16.06.2011

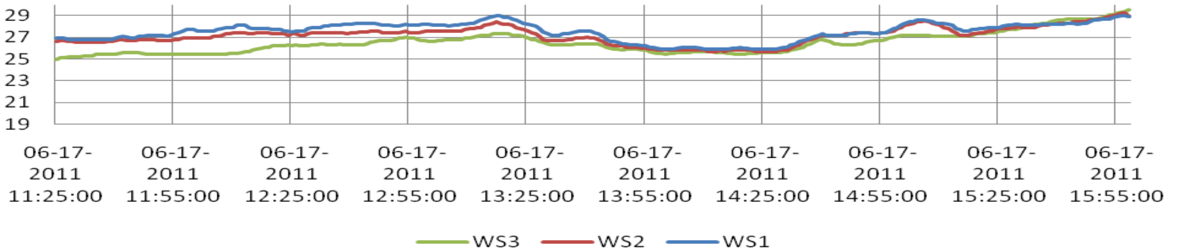


Figure 4 – Temperature °C/hour 17.06.2011

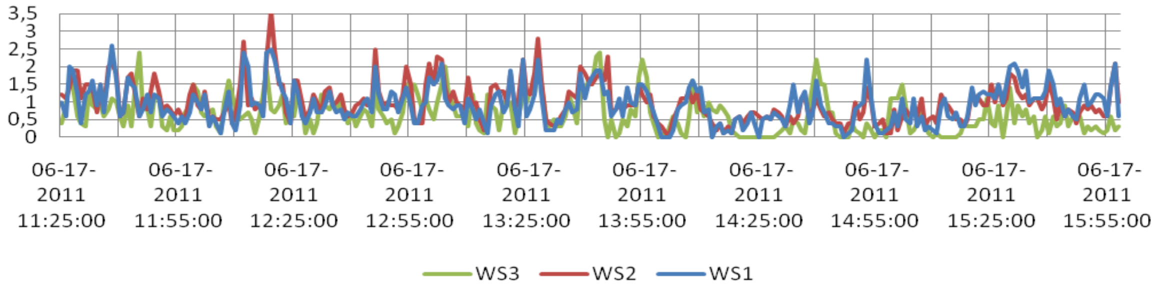


Figure 5 – Wind Speed m/sec 17.06.2011

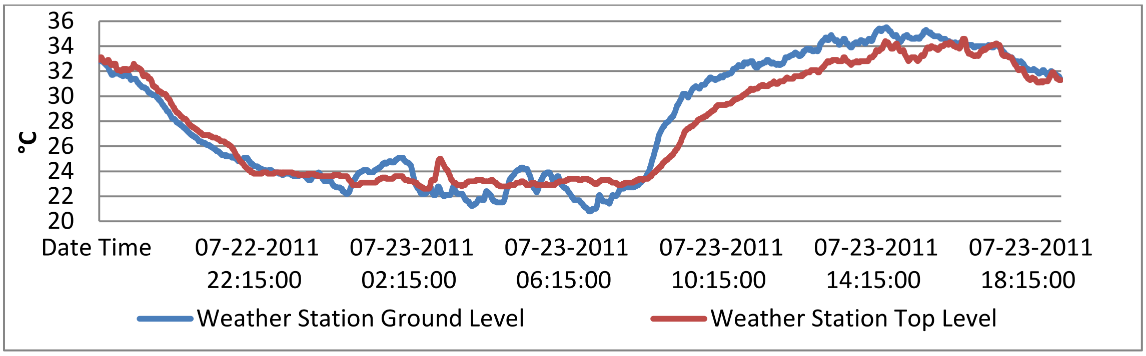


Figure 6 – Temperature °C/hour 22-23.07.2011 elevation difference between WS1-2 ≈ 20,0m

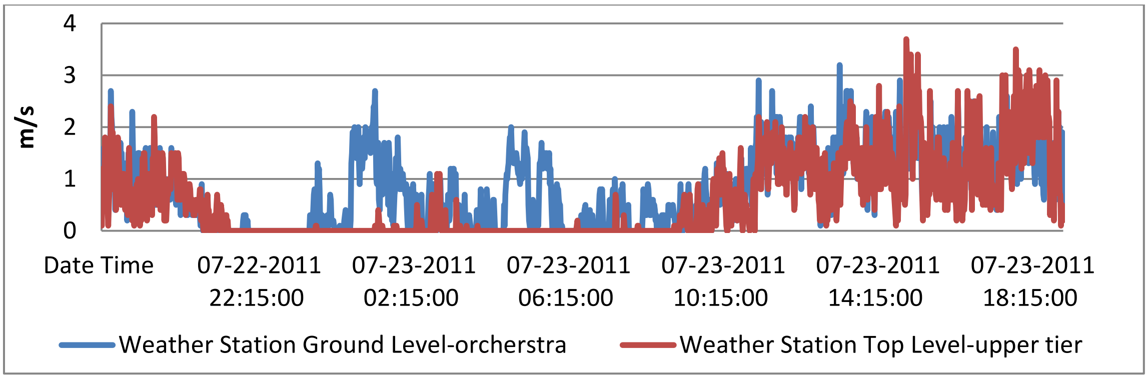


Figure 7 – Wind Speed (m/s) 22-23.07.2011 elevation difference between WS1-2 ≈ 20,0m

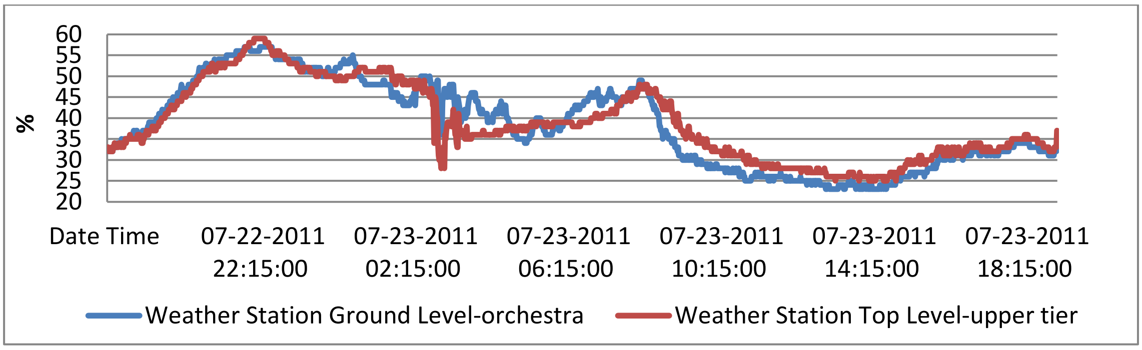


Figure 8: Humidity(%) 22-23.07.2011 elevation difference between WS1-2 ≈ 20,0m

3. Acoustic Measurement Results

3.1 Two-day Measurements Averages (16-17.6.2011)

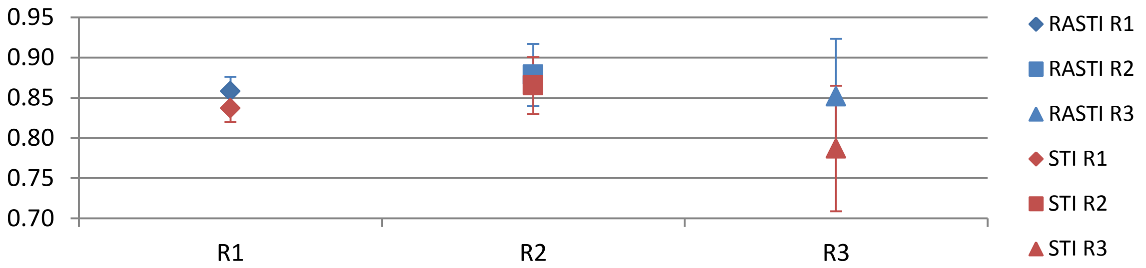


Figure 9 – Speech indices averages 16-17.6.2011

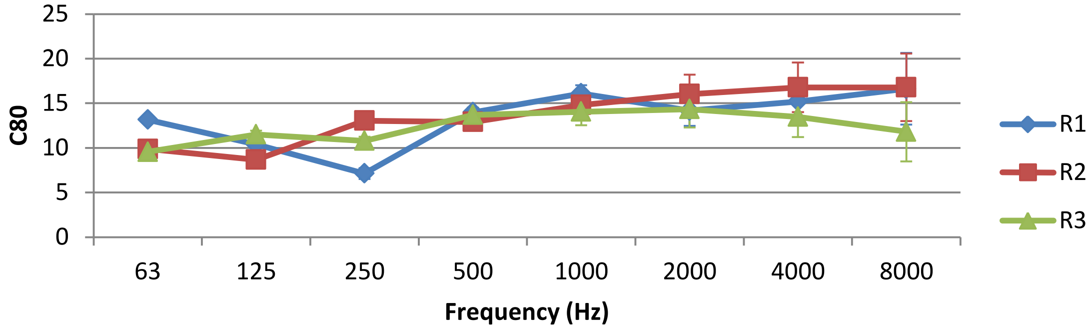


Figure 10 – C_{80} averages 16-17.6.2011

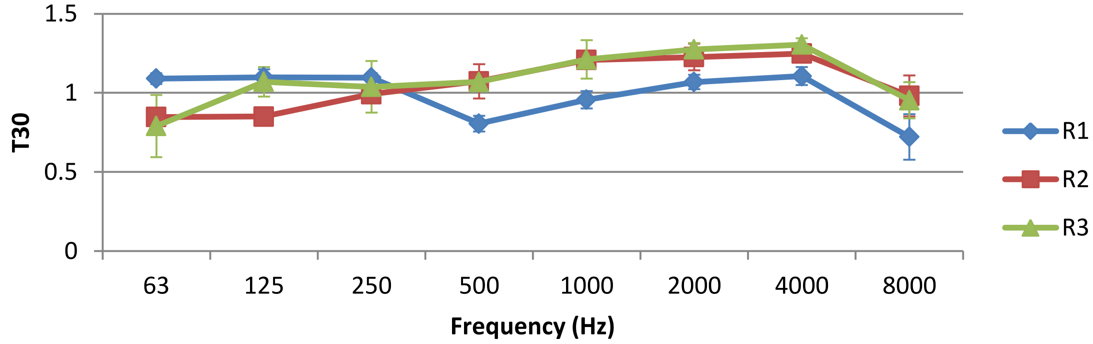


Figure 11 – T_{30} averages 16-17.6.2011

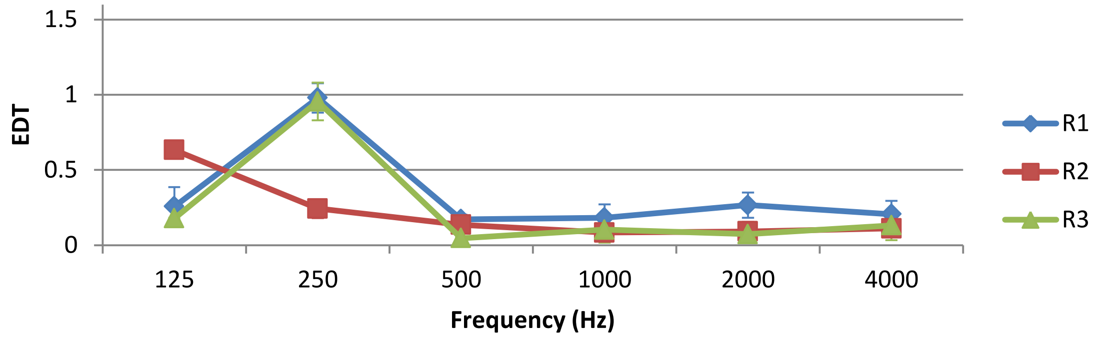


Figure 12 – EDT averages 16-17.6.2011

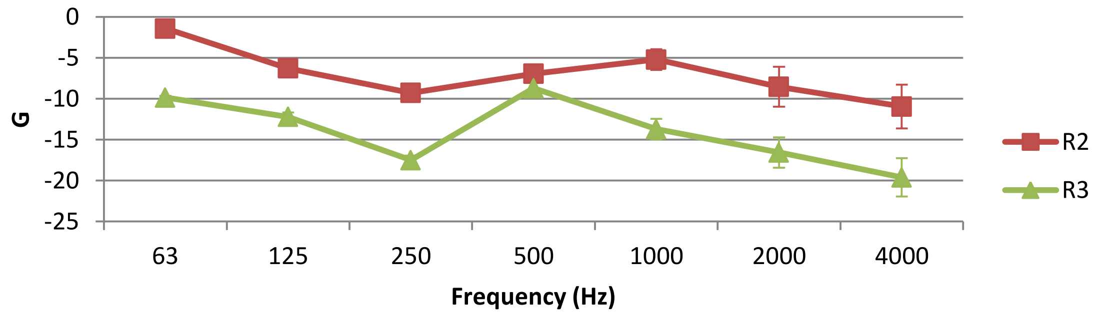


Figure 13 – G averages 16-17.6.2011

3.2 Hemispherical Sound Propagation Measurement

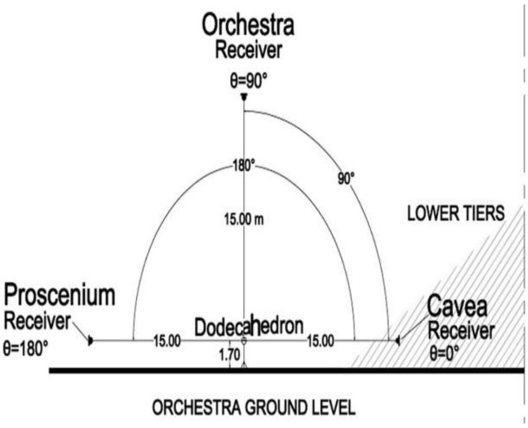


Figure 14a – Receivers' positioning

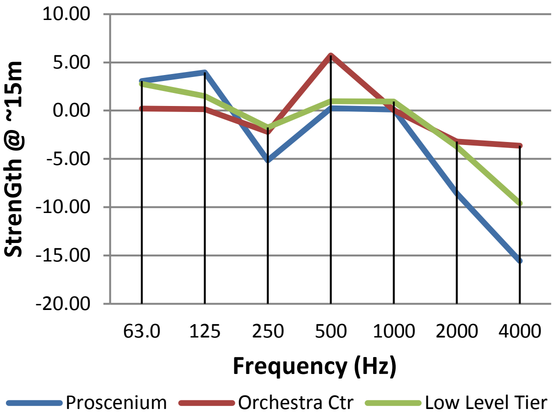


Figure 14b – G strength

The parameter G was measured at a z/y-axis hemisphere of ~15m radius with the receivers positioned as illustrated in fig.14a. Cavea Receiver: 0° (lower tier level), Orchestra Receiver: 90° above the dodecahedron, Proscenium Receiver: 180°, with wind velocity 0,4-1,1 m/sec and wind direction N. In fig.14b are presented the differences found due to ground and tiers reflections and weather conditions.

3.3 Cavea Walkthrough Measurements

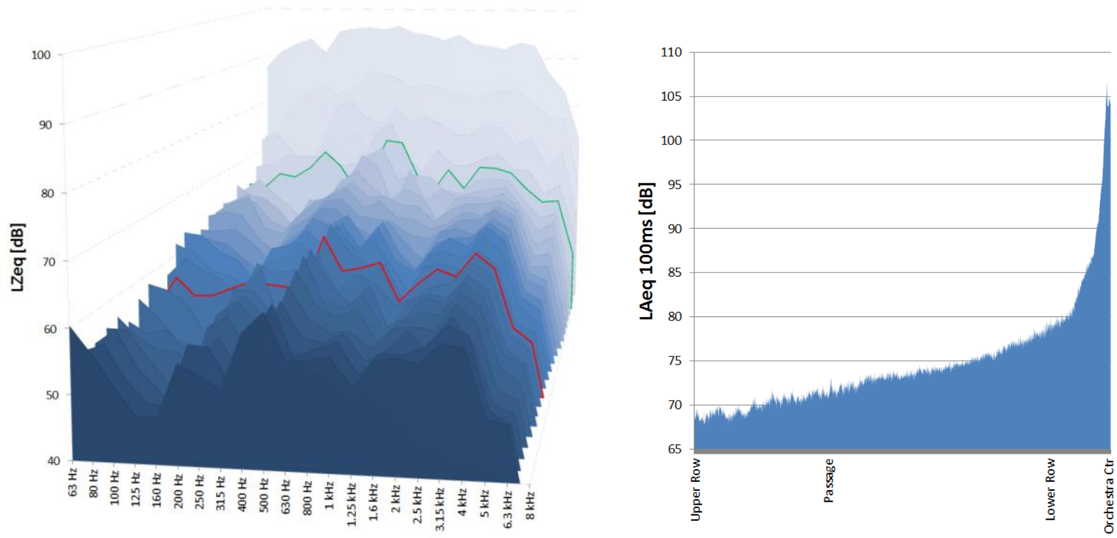


Figure 15 – Logging measurement of a cavea 'walkthrough' from top to the orchestra, in order to measure the freq. response difference at varying distance/height. At the left figure the red and green line correspond to the passage and lower row respectively.

3.4 Unoccupied v Occupied State Measurement Comparisons

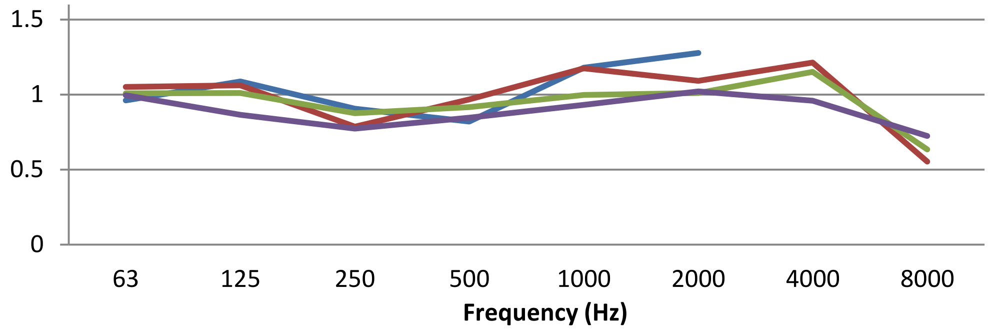


Figure 16 – Unoccupied v Occupied Relative Comparison of T30 at R2

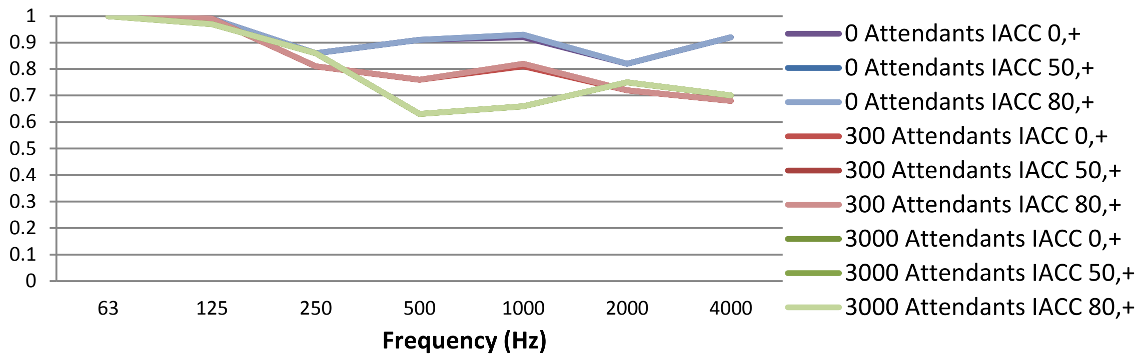


Figure 17 – Unoccupied v Occupied Relative Comparison of IACC 0,+ / 50,+ / 80,+

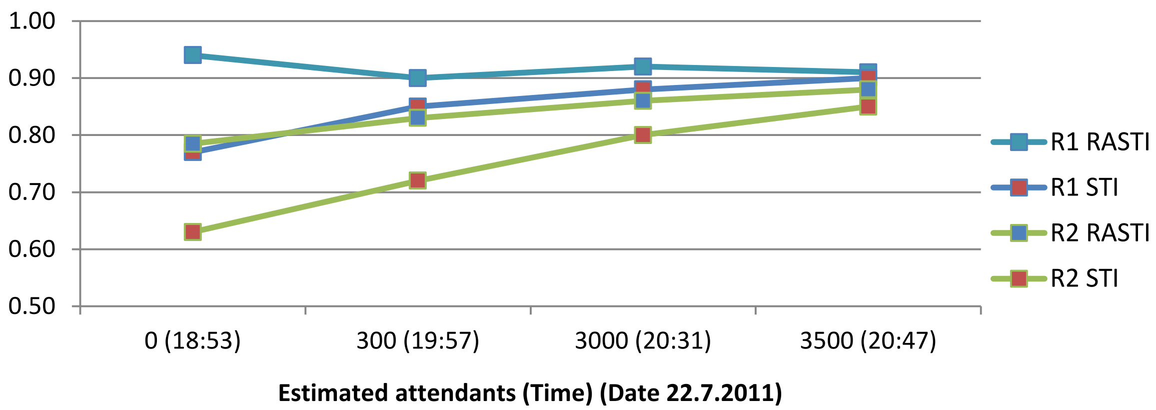


Figure 18 – Unoccupied v Occupied Relative Comparison of Speech Indices, (cushions were laid at lower tier level rows)

Meteorological Data	**0 attendants(18:53)**	**300 attendants(19:57)**	**3.000 attendants(20:31)**	**3.500 attendants(20:47)**
Temperature-orchestra level	31,6°C	29,1°C	27,3°C	26,6°C
Temperature upper tier level	32,2°C	30,2°C	28,1°C	27,3°C

Wind Velocity-orchestra level	0,8 m/sec	0,7 m/sec	0,7 m/sec	0,6 m/sec
Wind Velocity-upper tier level	0,5 m/sec	0,5 m/sec	0,9 m/sec	0,6 m/sec
Wind Direction-orchestra level	NE	NE	ENE	NE
Wind Direction-upper tier level	NE	NE	NE	NE
Humidity-orchestra level	35%	44%	49%	52%
Humidity- upper tier level	35,2%	43%	48%	51%

Table 2 – Meteorological Parameters 22.7.2011

4. Conclusion

This study shows that during the theatrical performances with the presence of large number of audience, the intelligibility of performer's speech increases significantly at all measured audience positions. Although the individuals that occupy the lower/closest seats perceive speech better in absolute terms, the relative contribution of the occupied state of the theatre is more advantageous at higher positions. In addition, although IACC values and reverberation times T_{20}, T_{30} were found significantly decreased, on the other hand, the state of occupancy did not appear to be equally important when comparing the parameters of C_{80} and Ts.

Since Phase B occupied state results are based on single 'one-shot' measurements with minimum statistical averaging compared to extensive Phase A sampling, further future validation of the 'occupied' measured data is recommended. An issue that has to be better accounted for, is the increased background noise of typical Greek summer cicadas that proved to compete quite well with the SNR tolerance margin of the measurement system, resulting to the final exclusion of the respective frequency bands at some measurement results.

With regard to the local meteorological parameters, WS3 at upper tier level with elevation difference approximately 20,0m compared to orchestra level WS1, demonstrated an average difference of 2,0°C (WS1-2,0°C) at morning hours approximately at 08:30-11:30, convergence temperatures in the afternoon and divergence of about 2,0°C at night with warmer the upper tier (WS1+2,0°C). Also, both stations WS1 and WS2 at orchestra level demonstrated an average difference of 0,5°C with elevation difference 5m with warmer the WS1. At morning hours, an increase of wind velocity of 3-4m/sec was also observed, that faded away at the afternoon/evening hours. Wind directions are mostly N, NE.

Photo 1- Orchestra Area: Dodecahedron, WS1, WS2, Orchestra Receiver 90° as fig.14a

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