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Subwoofer array design for optimal acoustic performance and minimal noise pollution in the Roman theatre of Italica, Spain.

Claus Köpplin Orrán[1], Luis Gomez-Agustina[2]
London South Bank University
School of the Built Environment and Architecture, 103 Borough Road, London, UK

Alvaro Grilo Bensusan[3]
INERCO Acústica S.L.
INERCO Acústica. Tomas Alba Edison, 2 (Isla de la Cartuja), Seville, Spain

ABSTRACT

Subwoofer arrays are widely used in live sound events. However, the performance of sound systems and the generated environmental noise pollution in the vicinity of Roman theatres is not well researched and documented. The investigation aimed to determine the most suitable subwoofer array configuration for an outdoor Roman theatre according to their low frequency coverage across the audience area and overspill on nearby residential areas. Performance suitability was determined by measuring the overall sound pressure (dBA) and spectrum levels of the arrays within the audience area at several locations representative of nearby residential areas. The Array Performance Rating (APR) was calculated for each array configuration to complement performance assessments. Results showed a notorious difference between coupled and uncoupled arrays, as well as between ground-based and flown subwoofer configurations. It was proven that the flown point source array offered overall less sound pressure levels and spectral variability in the audience plane and it caused the least environmental noise pollution. The conclusions drawn from this study can provide valuable guidance applicable to future sound system deployments and reconstruction projects of ancient outdoor theatres of similar architectural and environmental characteristics.

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[1] info.clauskopplin@gmail.com
[2] gomezagl@lsbu.ac.uk
[3] agrilo@inerco.com

1. INTRODUCTION

The number of outdoor music festivals increases every year, which has consequently resulted in a higher demand for new venues. A fundamental task for the sound system's engineer is to deliver uniform sound quality across the entire audience area. This is mainly achieved by a proper physical arrangement of loudspeakers. Investigations carried out by Olson in 1957 [1], [2] provided meaningful information regarding the importance of loudspeaker positioning. Since then, more research has been carried out in this field and designing a sound system has become highly rigorous.

The low frequency range between 20 Hz and 125 Hz is very important for the perception of quality in live sound reinforcement performances. This range is more problematic due to low-frequency propagation being harder to control and travelling further into the environment than higher frequencies, as well as air absorption not being significant in this range. Hence, special attention is required when designing and deploying a subwoofer system for minimizing noise pollution. Moreover, as more live music events are nowadays hosted in unusual spaces, their acoustics and sound system's suitability should be carefully assessed beforehand. Noise pollution generated by outdoor sound systems has become a critical aspect to music events as they are sometimes hosted in venues next to noise sensitive areas. Governmental bodies and independent organisations have applied regulations and noise limits in the last decades in attempt to minimize the negative impact on local residents [3]. However, they do not fully encompass the entire acoustical parameters of music events under their legislation.

The aim of the project was to evaluate the suitability of three representative subwoofer array system configurations in the Roman theatre of Italica in Seville, Spain. The identified optimal configuration achieving the best acoustic quality and lowest noise pollution, will contribute to provide an enhanced vivid and real experience of what a dramatic representation in Ancient Rome was, promoting culture and contributing to a better understanding of the Roman life.

This paper reports for the first time in the literature, an investigation into the effects that different subwoofer configurations have on acoustic quality and environmental noise pollution from sound system installed in ancient outdoor venues. The novel insight, findings and methods reported can contribute to future archeo-acoustics investigations such as the anastylosis of the *scaenae frons* [4] and applied to same-shaped venues regardless their antiquity.

2. THEORETICAL BACKGROUND

The range between 20 Hz and 125 Hz is an essential frequency band for sound systems in musical applications and therefore, controlling the directionality of the system is useful to avoid unnecessary interaction with the venues' shape and to minimize unwanted noise pollution [5].

Since the beginnings of sound reinforcement, subwoofer systems have been deployed on the ground in different configurations. However, with the development of technology and logistics, sound system engineers started to 'fly' the subwoofer arrays. This positioning of subwoofer still divides the industry due to a common belief of efficiency loss [6].

Sound system configurations can be divided into two groups: coupled and uncoupled arrays.

The ground-stacked point source array consists of a line of subwoofers in which delay can be applied to achieve the desired coverage pattern. By curving the system, the directivity can be decreased and therefore the coverage broadened. Another way of controlling coverage is by making the array cardioid. There are different ways for creating a cardioid array, depending on the number of subwoofers used. A common cardioid array is to have three or four subwoofers in which two or three loudspeakers will be facing one direction, and another will be turned around and delayed to the distance of the acoustic centres for maximum cancellation in the rear. These are coupled arrays.

Comb filtering is expected in the case of uncoupled arrays since the speakers work as units and there is a significant amount of interaction between them. The most common configuration is Left-Right (LR) subwoofer arrays, either ground-staked or flown.

There is a variation of the LR array which consists in placing the subwoofers behind each other in order to make each side more directional, known as end-fire array, following the same principle as the second-order gradient loudspeaker presented by Olson. Nevertheless, LR arrays will always generate a certain amount of comb filtering.

In 1973, Olson [1], [2] proposed a technique for controlling the loudspeaker's directionality at low frequencies. This was done by physically separating two or more loudspeakers by a given distance as well as functioning with different phase or power.

2.1 Quantification of subwoofer arrays' performance

Adam Hill [7] presented a numerical way of expressing the suitability of a subwoofer sound system inside a given venue. This is given by a coefficient called Array Performance Rating (APR), which is made up of three terms: tonal consistency (SV), acceptable system headroom (HR), and audience & FOH level consistency (AUD). The APR final value will range from 0 to 1, being 1 the best results achievable.

Once all three terms have been obtained, they are introduced in the following equation. There is a weighting value for each term which will be set to one third as to give them the same relevance.

$$\mathrm{APR} = W_{SV}\left(10^{\frac{-SV}{20}}\right) + W_{HR}\left(10^{\frac{-\Delta HR}{20}}\right) + W_{AUD}\left(10^{\frac{-\Delta AUD}{20}}\right)$$

Equation 1: APR calculation [7].

3. LITERATURE REVIEW

In a recent investigation [8], the acoustic properties of a Roman amphitheatre were obtained through 3D acoustics computer simulations. The study investigated the impact that several proposed interventions would have on the acoustical quality in the seating area. The validated model and findings obtained were intended for future work such as the auralisation of the space or the investigation of the influence of audience in the *cavea* (audience seating area).

Figure 1: View of the theatre of *Italica* from the *cavea*.

Another investigation related to the project was the ERATO project [9], which worked to an international scope encompassing several universities and independent researchers, carrying out investigations in numerous Roman theatres. Most of these projects investigate the frequency response starting at 125 Hz and some of them at 120 Hz.

Some investigations into the natural and virtual acoustics of ancient theatres [10], [11], [12] followed the relevant international standard ISO 3382 [13] and thus only considered frequencies above 125 Hz. Other researchers [14], explain that there is high uncertainty when collecting reliable data from acoustic measurements within the low-frequency range, and that the results from simulation softwares are not consistent [15], or that there is no relevance in studying below 125 Hz as it is lower than the fundamental frequency of the male voice, and therefore no relevance in studying for the purpose of their projects [16].

Fundamentally, as the main objectives of past projects have focused exclusively on the original use of Roman theatres (unamplified speech performances), and assessment of their current acoustical characteristics (speech intelligibility, clarity, definition, etc.), it is understandable the frequency range chosen for the investigations. Due to the expansion of show genres taking place in these venues, such as amplified music concerts and dancing festivals, it is now necessary to assess the low frequency acoustic performance of the sound system in the venue for the intended use.

The Guidelines for Community Noise [17] have permitted Europe to become one of the most forward-thinking continents in terms of controlling noise pollution. However, these guidelines are not perfect for all cases since most regulations are based on A-weighted equivalent continuous level (L_Aeq_T) measurements, which do not permit low frequencies in musical context to be represented in their totality, which leads to future work still to be done in the field of outdoor entertainment events [3], [18], [19]. There is also a tendency within the European countries to set limits to noise generated from outdoors sources in relation to ambient noise limits. These limits range from 3 dB to 15 dB above the ambient level. This can be considered a reasonable trend since different countries have considerably diverse background noise levels [3].

4. METHODOLOGY

Three subwoofer arrays were deployed inside the theatre and acoustic measurements were carried out in the *cavea* and in nearby noise sensitive areas. In order to guide the study and better analyze the results gathered, four objectives have been set:

- Do flown subwoofer arrays loose 3 dB due to no ground reflection?
- Is there a significant difference between coupled and uncoupled subwoofer arrays?
- Which array generates less noise pollution outside the venue?
- Does the coverage pattern and height of the array influence in the noise pollution emitted?

The sound systems were designed using the software Soundvision, and the loudspeakers chosen were the SB28, both from L-Acoustics [20]. A 3D geometrical model of the Italica theatre was reproduced based on the original model taken from the literature [8] which represents the present status of conservation of the theatre as seen in figure 2.

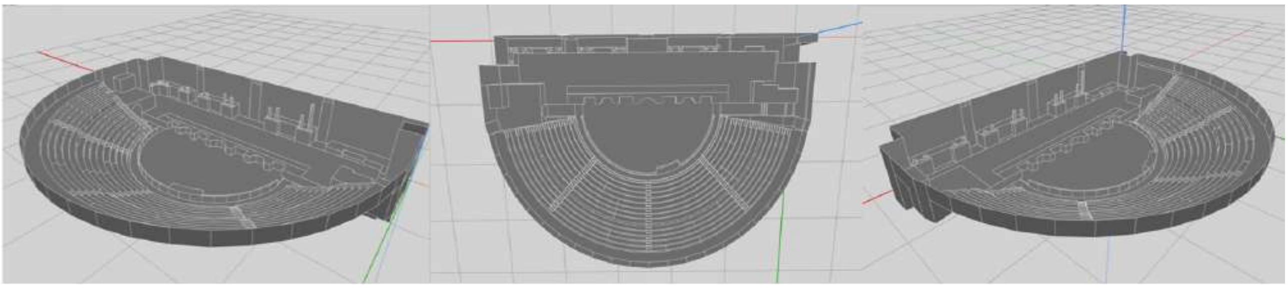


Figure 2: Different views of Italica's Roman theatre 3D model [8].

The first configuration, the ground-based point source array, was designed with three cabinets. The array was centered in front of the stage. Electronic delay of 3.3 milliseconds was applied to both the left and right subwoofer speakers in order to achieve the desired sound pressure level (SPL) coverage of 180 degrees, see Figure 3 (left).

The second configuration, the LR array, was composed of four cabinets, two per side. Both pairs were positioned at 6.75 metres from the centre of the stage. Although ideally, the number of subwoofers should have been the same for all the three arrays, the left-right configuration had to be arranged by adding one more cabinet so that both sides had the same number of loudspeakers. In the same way, it was not realistic to add a fourth cabinet to the flown and ground-based array since it would have provided an overload of sound pressure level not necessary for the venue.

The third configuration, the flown point source array, has a cardioid coverage pattern by having the lower cabinet being turned around and delayed by 3.3 milliseconds, causing the sound waves to propagate forward and cancel out most of the frequency content on stage. Due to limitations of preservation of the historic venue, the flown array's structure was positioned on stage, three metres behind where the other two arrays were positioned. The top of the array was rigged at six metres. This height corresponds to the stage back wall's height, see Figure 3 (right).

Figure 3: Ground-based point source array (left) and flown point source array (right).

4.1. Measurement locations

The responses were measured with a Beyerdynamic MM1 microphone and a portable computer running the acoustics measurement platform Smaart V8. Ninety reception points (microphone positions) were distributed to cover uniformly the seating area which allows for a good representation of the audience listening content [21]. Points were separated at least 2.5 metres away of each other, making a total of 75 points in the *cavea*, 10 points in the *orchestra*, and 5 points on stage (Figure 4, left). The height of the microphone capsule was 1.2 metres, as the usual audience position is seated, and recommended by the ISO 3382 [13].

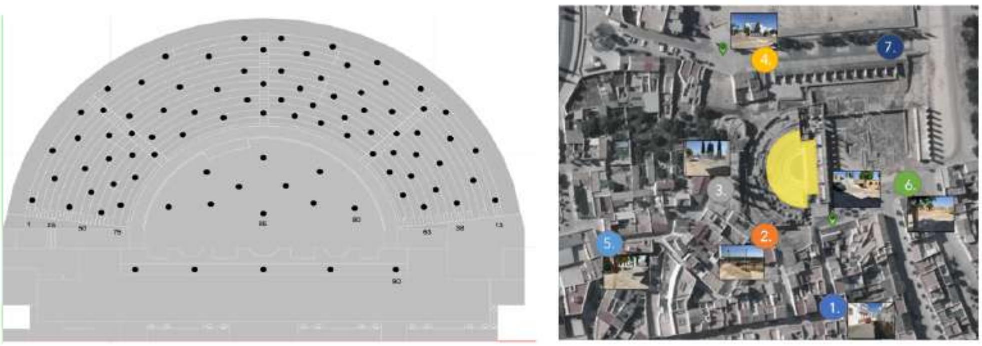


Figure 4: reception points distribution inside (left) and outside (right).

Seven receiver positions were chosen in the residential areas near the theatre, as shown in Figure 4 (right). These allowed for a good representation of the noise sensitive areas and to understand how the sound energy propagates around the venue.

Environmental measurements were taken according to ISO 1996-2 [22] with two calibrated Solo 01dB class I sound level meters, both located at 1.5 metres above the ground and in the free field at least 3.5m from any reflecting surfaces were possible. The measurements were taken over two days. The first day was to measure background noise levels, in which 15 minutes were measured. This time frame would allow to capture five-minutes long measurement from which the average could be taken. The second day SPL were measured at the same locations when, the response of the different subwoofer arrays was measured. In this case, only five minutes were captured since the measurement signal (pink noise) is very stable over time. From all these measurements, one-minute-long sections with minor influence of the background noise will be extracted as representative values for later analysis.

4.2. Analysis of data measured inside the venue

The SPL measured data in the venue was analysed in four groups. The first group divided the measurement locations (black dots in Figure 5) in sections. The venue was split into four identical parts as shown in Figure 5 (left). This served to analyse the array coverage from left to the right side.

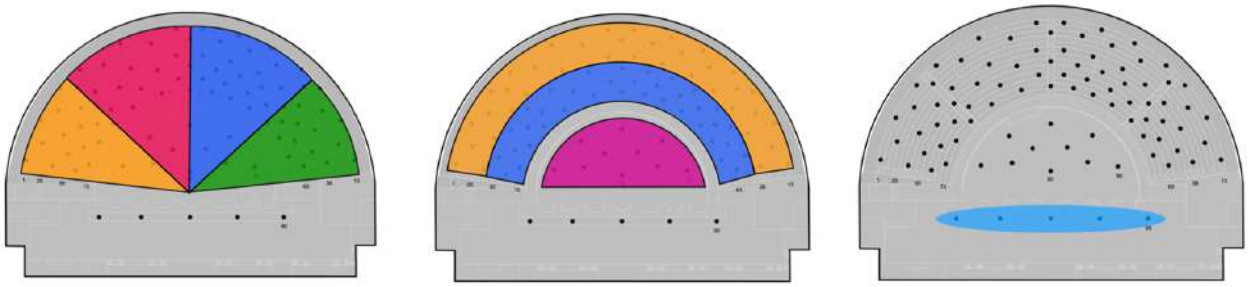


Figure 5: Theatre divided into sections.

The second method of analysis was to divide the theatre in three sections from the front to the back. This way, the closest section would be the *orchestra*, and the second and third would be the first and second half of the *cavea*, as shown in Figure 5 (centre). This way of analysis allowed to see the array's responses over distance.

The third method of analysis was to look at the stages' responses, Figure 5 (right). This allowed to assess the array's leakage onto the stage. Although the APR formula does not take into consideration the responses on the stage for the final result, and so does not the analysis made in this project, it will still be analysed as a relevant and directly related parameter to the positioning of the arrays.

The last method of analysis for the acoustic measurements was to compare the different array's responses over the entire audience (APR). This allowed to see the average responses and, combined with the standard deviation, a conclusion to which array has the less amount of variation as well as the best frequency response profile could be achieved.

5. RESULTS

Figure 6 displays the comparison of the frequency response for each subwoofer array averaged across all audience reception points. The left-right configuration can be considered the one with the flattest response of all three. The ground-based point source array displays lower values than the LR configuration and presents distinctive maximums and minimums. Lastly, the flown array showcases a faster roll off the higher frequencies.

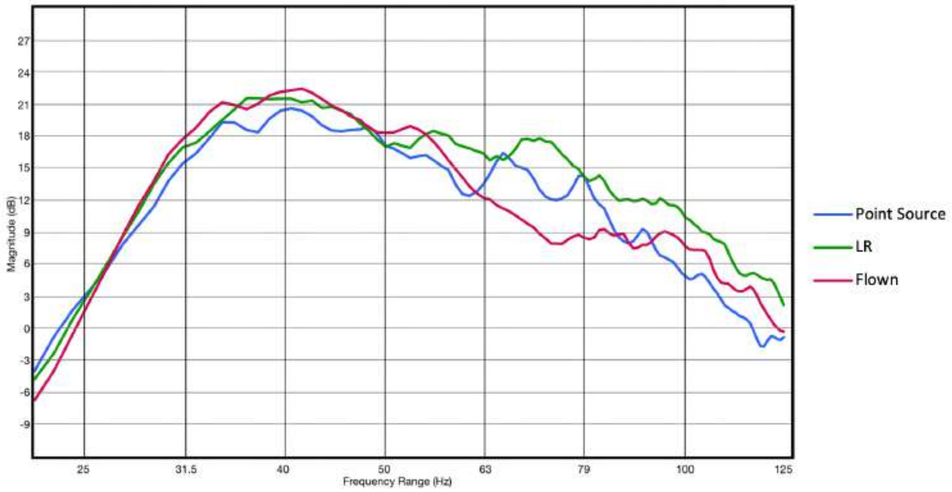


Figure 6: Magnitude over frequency response of the three subwoofer arrays.

There are two trends in the standard deviation of the averaged frequency responses (Figure 7, Left). The LR configuration presents the highest amount of level deviation, and the ground-based and flown array present similar responses up until 55 Hz, where the ground-based array continues with an increasing trend, and the flown array decreases its deviations.

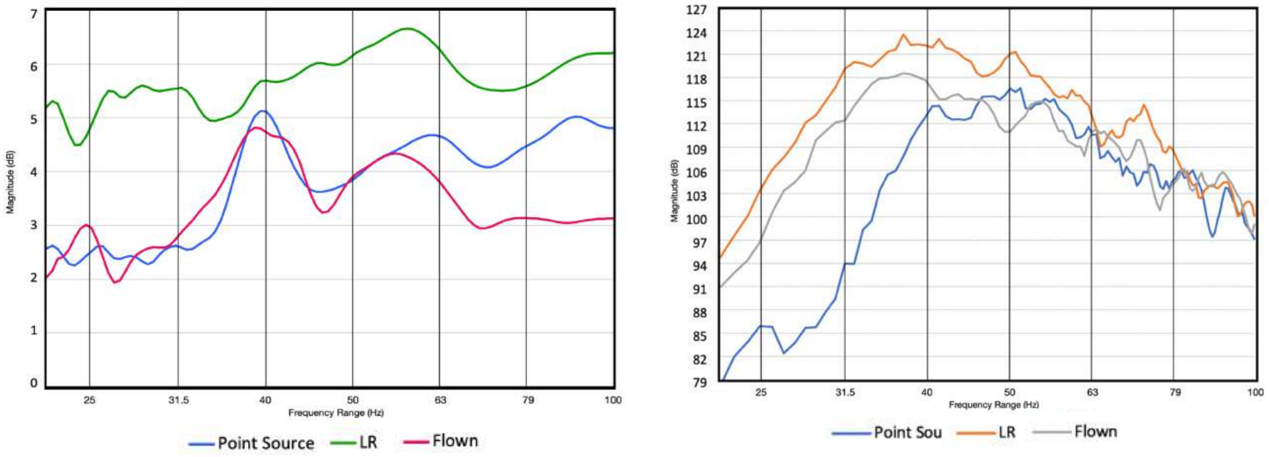


Figure 7: Standard deviation over frequency range of the arrays (Left). Magnitude over frequency response of the arrays (Right)

Regarding the frequency response on stage, Figure 7 (Right) shows the average response for the three subwoofer arrays. The two point source arrays (ground-based and flown) provide the most favourable results due to their cardioid pattern. As the LR array has symmetrical SPL propagation to the front and to the back, it is the one with more spillage on stage.

5.2. Environmental noise

Figures 8 and 9 display the frequency content from the two arrays configurations measured in different receptor points located outside the theatre. Figure 8 on the left shows the frequency response of receptor points 1, 2, 3, 5, (see points in figure 4), and the graph on the right contains the frequency responses of reception points 4, 6, 7 (see points in figure 4). The responses for the ground-based array tend to be less variant than the flown array. For both arrays, a decreasing trend can be found in points 4, 6, and 7.

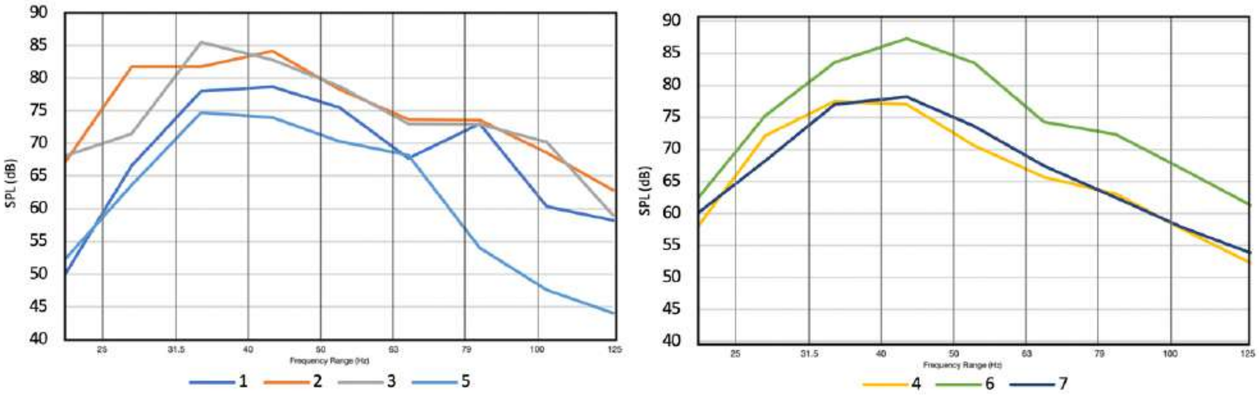


Figure 8: Frequency responses in residential area – Point Source Array

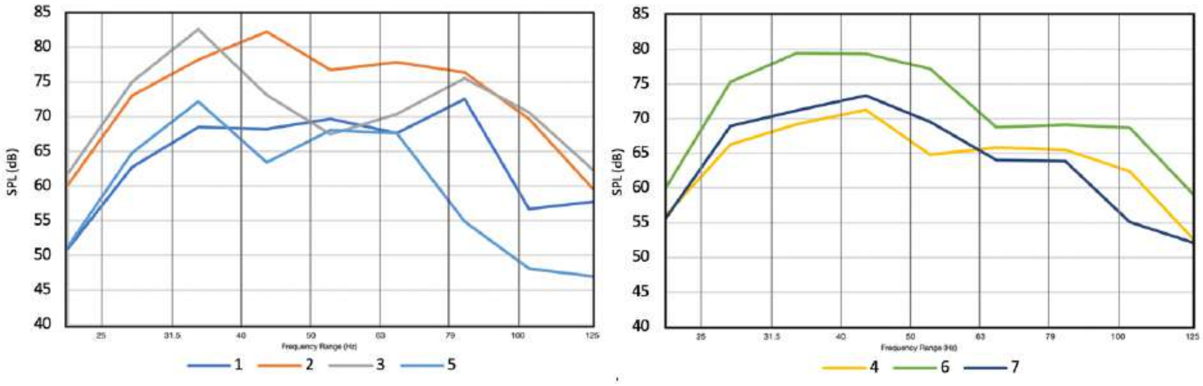


Figure 9: Frequency responses in residential area – Flown Array

Figure 10 displays the overall L_Aeq_{1min} measured values in all residential receptor positions for the background noise and when subwoofer arrays were in operation, as well as the standard deviation at each receptor point. It can be seen that background levels range between 55 dBA and 63 dBA. Values corresponding to the ground-based point source array reach higher levels than the flown array at all points, even though it was at ground height.

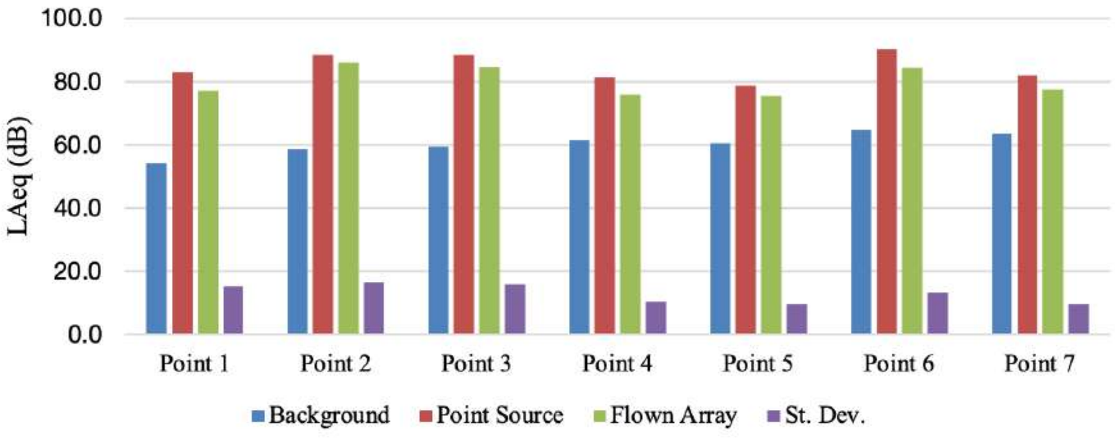
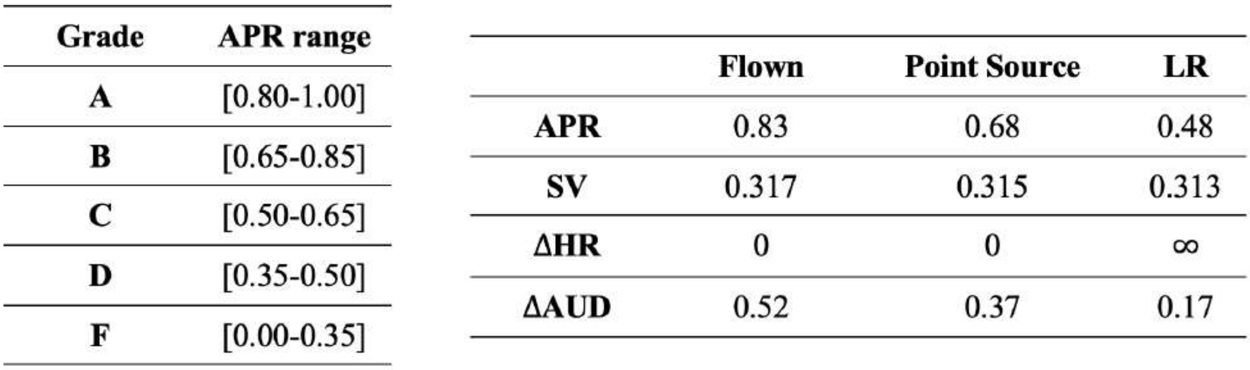


Figure 10: L_Aeq_{1min} of noise pollution over measurement locations.

5.3. APR results

Following the calculation in section 2.1, the APR for the LR array (0.48) falls within the *D* grade, being the worst results of all three arrays. The ground-based point source array achieves an APR of 0.68, which falls within *B* grade, being a better compromise than the LR array. Lastly, the flown array showcases the most favourable values (APR of 0.83), with just 0.41 dB of variance across the audience area, being the lowest of all three arrays. This is the reason why the flown array falls within the *A* grade.

Table 1: APR Results (Left Table [6])



Grade	APR range
A	[0.80-1.00]
B	[0.65-0.85]
C	[0.50-0.65]
D	[0.35-0.50]
F	[0.00-0.35]

	Flown	Point Source	LR
APR	0.83	0.68	0.48
SV	0.317	0.315	0.313
ΔHR	0	0	∞
ΔAUD	0.52	0.37	0.17

6. DISCUSSION

Does the flown subwoofer array loose 3 dB due to no ground reflection?

The flown array follows the trends of the other two configurations in most of the frequency range. However, the only part in which a 3 dB decrease can be seen in comparison to the ground-based point source is between 63 and 83 Hz. Despite this, the $SPL_{20\text{-}125Hz}$ for the arrays are 108 dB for the ground-stacked point source, 110 dB for the LR configuration, and 109 dB for the flown array.

Even if it was claimed that these levels are an average of the whole audience, there is not a 3 dB difference in the *orchestra* alone either. Therefore, the flown subwoofer array does not loose 3 dB due to lack ground reflection.

Ground-stacked configurations tend to present higher front-to-back SPL level differences than flown arrays. In this case, the LR configuration has a level difference of 10 dB, the ground-based point source has a level difference of 6.1 dB, and the flown array has a level difference of 5.5 dB. This demonstrates that flown arrays have better front-to-back coverage.

Is there a significant difference between coupled and uncoupled subwoofer arrays?

The standard deviations of the three averaged frequency responses show that the uncoupled LR array has an average standard deviation of 5.7 dB, and in the coupled arrays 3.8 dB for the point source and 3.3 dB for the flown array. Additionally, the APR results showcase the two coupled arrays with grades A and B, and the uncoupled array with grade D, differentiating both array types. Hence, there is a significant difference between the two types of arrays.

Which array generates less noise pollution outside the venue?

The flown array has lower noise pollution level in all measured locations. In the case of the ground-based point source array, it contains more energy in the lower frequencies, especially in Locations 4, 6, and 7. The flown array instead enables the propagation of the frequency content between 80 Hz and 125 Hz due to it being higher and thus, permitting more higher frequencies to be propagated outside. In terms of levels, the ground-based has an average of 86 dBA across the measured locations and the flown array 82 dBA.

Do the coverage pattern and height of the array influence the noise pollution emitted?

It could be expected that the flown array would have had higher noise pollution levels due to it being flown and therefore, permitting more sound energy spilling out of the theatre, which is partly true. However, it showed lower levels than the ground-based point source array despite them having the same SPL inside the venue. Therefore, it can be stated that there is no direct relation between the coverage pattern and height of the array, and the amount of noise pollution emitted, in the given theatre. Moreover, the effect of cardioid pattern of the arrays can be seen in Figures 8 and 9, where the locations behind the loudspeaker arrays present preliminary less noise levels.

7. CONCLUSION

This project has presented an evaluation of three subwoofer array configurations installed inside a Roman theatre for acoustic quality and noise pollution at the audience area and in the residential areas respectively.

LR array configuration showed the highest sound level variability in the audience area, mainly because it is an uncoupled array. The power alleys and valleys (constructive and destructive interferences) inherent to the physical deployment create an uneven coverage for the audience, which might affect their experience during the show.

Although the ground-based point source and the flown array have similar responses, the ground-based array produces higher front-to-back level differences than the flown array. This can cause over exposure for the audience in the front rows, and a lack of sound pressure in the back of the audience. Moreover, the height of the array does affect certain frequency bands. The ground-based array has more energy between 20 Hz and 60 Hz, and the flown array enhances the frequencies above 75 Hz. However, there is no proportional relation found between the height of the array and the amount of noise pollution emitted since the flown array displays lower levels than the ground-based array.

Lastly, APR results demonstrate the difference between coupled and uncoupled arrays, giving the two coupled arrays the best results (grades A and B) and the uncoupled array a D grade. Furthermore, it displays the difference between a ground-based and a flown point source array. As the flown array has less front-to-back SPL difference, the flown array achieves the best performance.

Overall, both the analysis of the acoustic measurements and the APR results showed that the flown array has the most favourable response in the theatre and in the nearby noise sensitive areas. Hence, making this subwoofer array the most suitable for the Roman theatre of *Italica*.

It is expected that the novel information and finding provided by this research will aid or serve as foundation to investigations into sound systems in Roman theatres. Suggested continuation further work includes: Performance of subwoofer arrays when the audience is on an angled plane. The effects of induced vibration from low frequency sound systems on the integrity of ancient venues. Implementation of acoustical materials in the anastylosis of the *Scaenae frons*. Subjetive and objective effects of noise pollution generated from Roman theatre sound system on local residents.

The novel insight, findings and methods reported can contribute to future archeo-acoustics investigations such as the anastylosis of the *scaenae frons* [4].

8. ACKNOWLEDGEMENTS

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