HOW DID EPIDAURUS SOUND WHEN IT WAS FULL? DIRECTIONAL MEASUREMENT OF IMPULSE RESPONSE FOR AN IMPROVED COMPUTER MODEL

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1 INTRODUCTION

Why is it that for centuries, the acoustics of ancient amphitheatres have captured the public imagination? Popular opinion has regarded these places as acoustically ‘special’. They are often mythologised as places where you can hear a pin drop or a whisper from the stage, even at the very back of the theatre. There is a perception that ancient Greek designers had a mystical understanding of acoustics which has since been lost, although in practice it seems obvious that the acoustics were merely a result of the only geometry capable of providing reasonable sightlines for a very large audience with the limited building options available 2,500 years ago.

We sometimes forget, however, that our typical modern-day experience of ancient amphitheatres is of empty spaces with no audience, and often with much of the original structure missing.

Figure 1 – The Large Theatre at Epidaurus [1]

Several researchers have conducted extensive acoustic surveys of ancient amphitheatres, including Gade and Angelakis [2] and Hak et al at the University of Eindhoven [3]. Their research projects have used computer models based on single-channel measurements in empty theatres. These single-channel measurements, however, provide no direct information as to the direction from which individual reflections arrive.

As consultants, we have a keen interest in deriving as much information as possible from sites where the time available for surveys is often extremely limited. In this case we owe thanks to Ecophon for their help in arranging access to the Large Theatre at Epidaurus to take measurements early in the morning before the site was fully open to tourists. Even so, we had very little time on site in quiet conditions, so we recorded directional impulse response using a Soundfield microphone and multichannel recorder for later analysis. The results were used to calibrate an acoustic computer model of the amphitheatre using CATT-Acoustic software. Once calibrated, this model became the basis for investigating the acoustic effects of adding a full audience and an upstage skene building.

2 MEASUREMENTS

2.1 Measurement methodology

We took a series of 4-channel audio recordings of balloon bursts using a Rode NT-SF1 Soundfield microphone and a Sound Devices MixPre 6 digital audio recorder. The NT-SF1 is an A-format microphone with a tetrahedral array of four cardioid capsules, as shown in Figure 2. The complete measurement setup is shown in Figure 3. The audio was converted and stored in full-matrix B-format using the Ambisonic decoding module on the MixPre 6 recorder. We took measurements at the receiver positions shown in Figure 4.

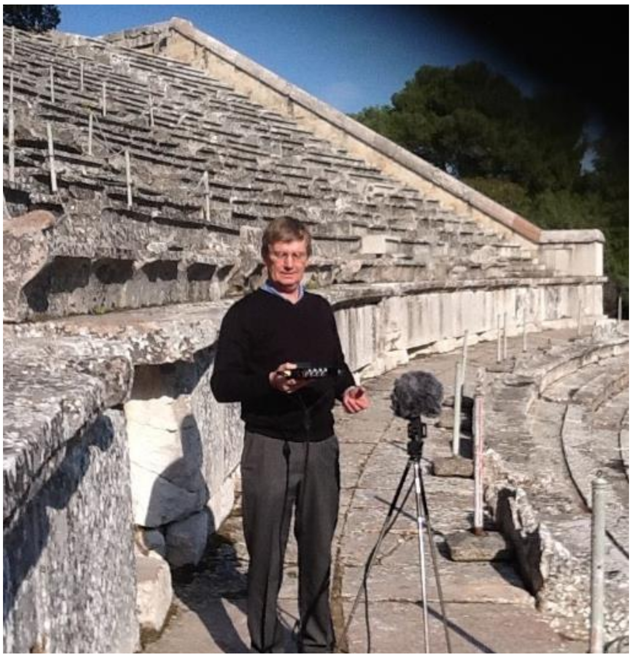

Figure 2 (left) – Rode NT-SF1 Soundfield microphone without cable or windshield
Figure 3 (right) – Soundfield microphone with windshield and audio recorder

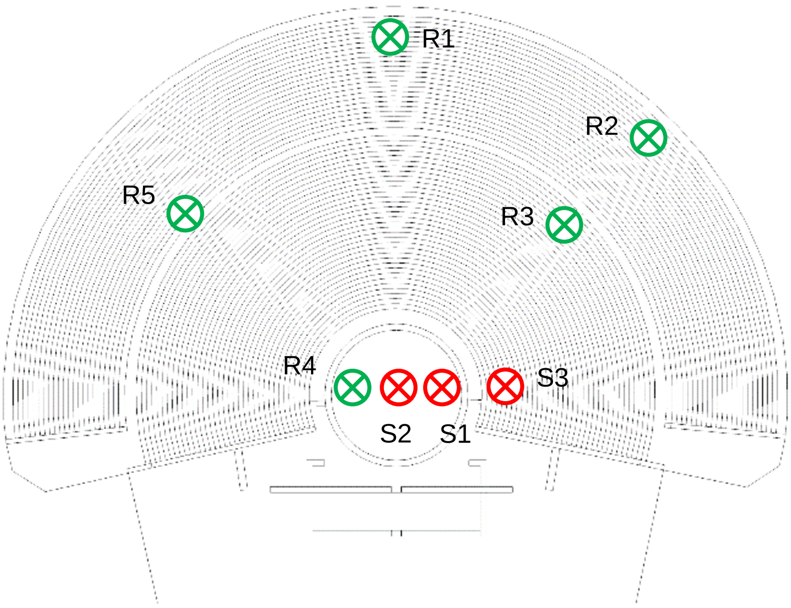

Figure 4 – Plan of amphitheatre showing receiver positions in green and source positions in red

For each of receiver positions R1 to R3 we took measurements with the source centre stage (S2) and 5 metres to the actor's right of centre (S1). To test cross-stage reflections, we took measurements with the source centre stage (S2) and the receiver 5 metres to the actor's left of centre (R4).

We analysed the recorded decays using the CATT ReflPhinder module within CATT-Acoustic. This allowed reverberation time and clarity measurements to be taken from the recorded decays. Directional analysis of reflections could also be undertaken using the rotating sector microphone feature.

2.2 Measurement results

Figure 5 shows the average measured T_{30} reverberation times at positions R1 to R3 from source position S1 on stage. The results correspond well with measurements previously taken in the theatre of Epidaurus by Gade and Angelakis [2] and Hoekstra, Nicolai et al [3].

Variation between measurements is relatively low at 500 Hz and above but increases considerably at low frequencies due to poor signal-to-noise ratio. This is to be expected in an outdoor environment with some wind noise, particularly given the relative lack of low-frequency energy in balloon bursts.

C_{80} clarity measurements, logarithmically averaged from octave-band results between 250 Hz and 2 kHz, varied from 11 dB to 14 dB at receiver positions R1 to R3, with an average result of 13 dB across all measurements at these positions. This again corresponds reasonably well with previous measurements.

While we would not claim that T_{30} or C_{80} are the acoustic parameters most relevant to this type of space, these results provide a useful comparison to measurements by others to validate our measurement methodology. They do not, however, provide a full picture of acoustic conditions in the amphitheatre. It is important to note in particular that unlike an enclosed auditorium, the strength of reflected energy is substantially lower than that of the direct sound.

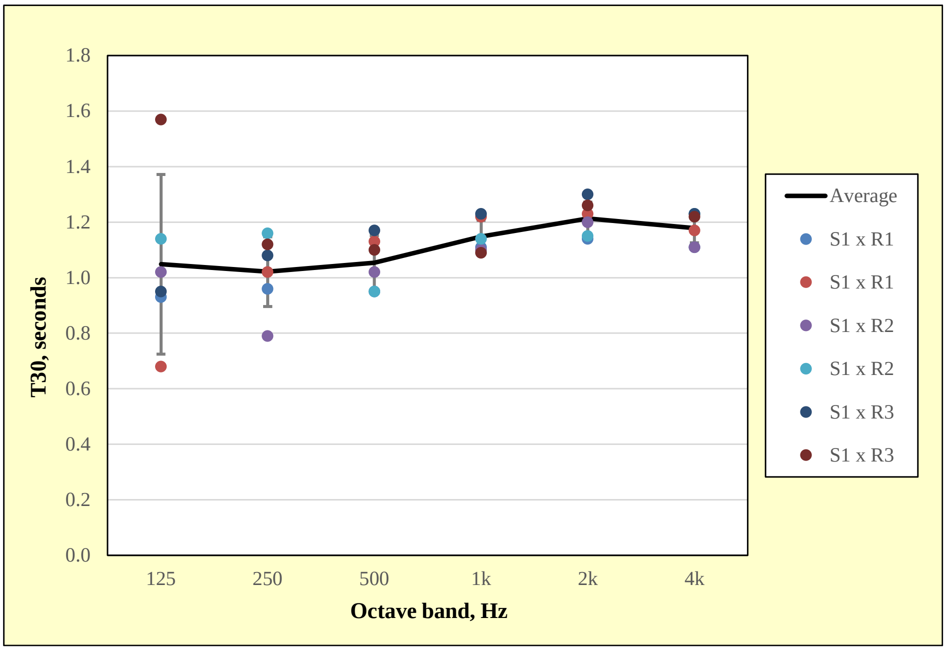

Figure 5 – Measured T30 reverberation times in amphitheatre

Figure 6 shows a comparison of recorded impulse responses from source position S1 to receiver positions R2 and R3, which are both at approximately 45° to the centre line.

Figure 6 – Echograms of recorded decays from S1 to R2 (top) and R3 (bottom)

These both show a steep fall-off in sound level within approximately 20 to 30 ms of the direct sound. The severity of this initial fall-off is reflected in the centre time (Ts) results, which are approximately 14 ms at R2 and 16 ms at R3. Measured Ts values varied throughout the amphitheatre but generally did not exceed 25 ms.

2.3 Directional analysis of reflected sound

Directional analysis of the recordings confirms expectations that most early reflected sound arriving within 50ms of the direct sound at these receivers are off the stage floor, and then off the seating tiers immediately behind the receiver. Naturally, therefore, there are fewer rear reflections at positions R1 and R2 at the top of the seating rake than at R3 further down. R3 also receives strong rear reflections from the upstand to the rear of the diazoma (horizontal aisle), which is pictured in Figure 3.

The fanned shape of the amphitheatre tiering provides very little early lateral reflected energy to receiver positions beyond the downstage edge of the orchestra. As a result, there is relatively little variation in any of the early reflected energy measures between receivers in the far field.

We observed with interest a relatively strong cluster of reflections at position R1 arriving from the direction of the stage approximately 85 ms after the direct sound. This is shown circled in Figure 7. Cross-referencing with our CATT-Acoustic model indicates that this is due to reflections off the remains of the skene walls behind the stage. Figure 8 shows a CATT-Acoustic time trace with first-order reflections off the skene walls clearly visible.

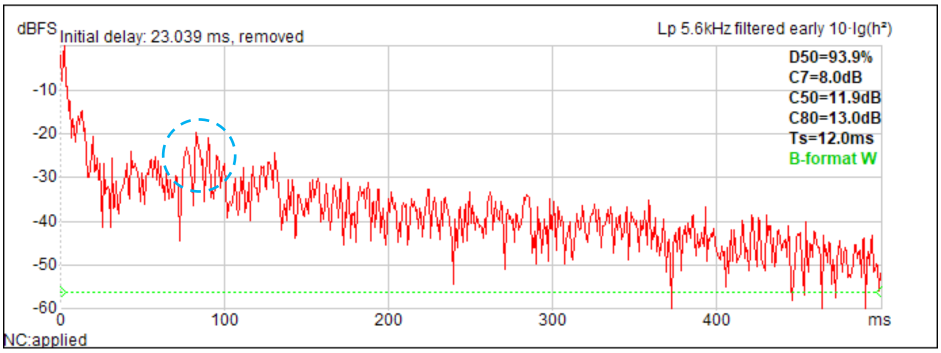

Figure 7 – Echogram of recorded decay at R1 with 85ms reflections circled

It follows that as the source moves closer to the skene, these reflections will occur sooner after the direct sound and a movement of only a few metres will being these reflections within 80 ms of the direct sound, thereby causing a sudden increase in C_{80}. As the source approaches a position 8 metres from the skene there will be a similar sharp rise in C_{50} and D_{50}. For this reason we consider that Centre Time Ts is a more useful parameter for evaluating clarity in this type of auditorium. We should also be aware that, perhaps because of the difficulty of achieving intelligibility in such large spaces, ancient Greek drama was delivered in a very stylised form of speech somewhere between declamation and chant, so that the commonly assumed cut-offs of 50 ms and 80 ms for “helpful reflections” probably do not apply.

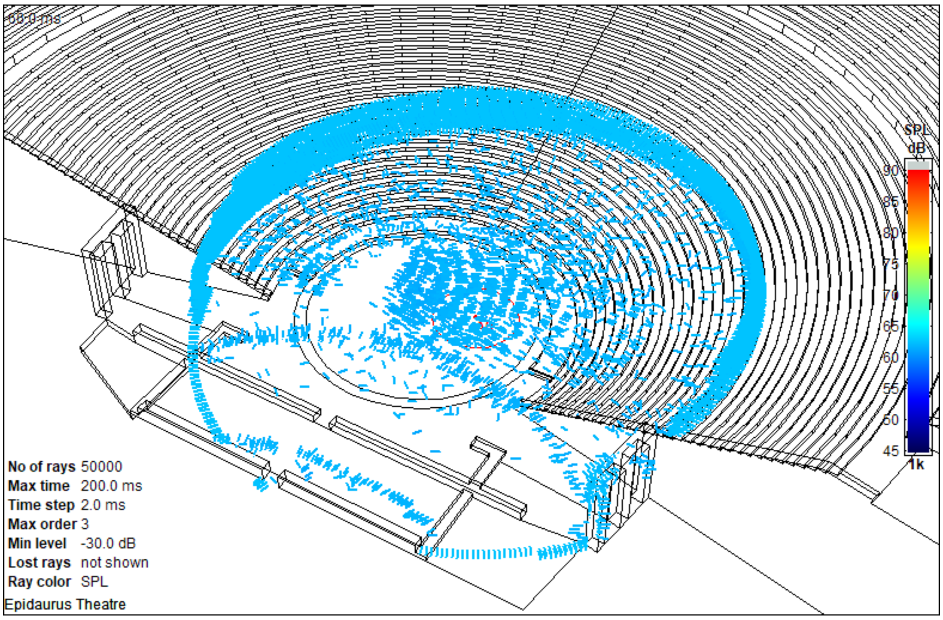

Figure 8 – CATT-Acoustic time trace showing reflections off remains of skene wall

3 MODELLING

3.1 CATT-Acoustic model

We created a model of the amphitheatre using CATT-Acoustic geometrical acoustic software, based on documented dimensions[4], supplemented with measurements taken on site. For simplicity, we modelled continuous tiers with no stepped gangways. As discussed in the previous section, acoustic reflections from the existing skene footings were found to be significant in the on-site measurements at position R1 so these were included in the model. Sources and receivers were positioned in the model to match the on-site measurement positions.

The TUCT engine of CATT-Acoustic uses ray / cone splitting for scattering prediction, which preserves the specular reflection path and generates new rays or cones for scattered reflections. This provides much greater determinism and repeatability when calculating both early and late reflected sound in an open model compared to those modelling methods which use mostly random scattering.

We calibrated the acoustic model with reference to the on-site measurement results. Such calibration not only requires consideration and adjustment of absorption coefficients but also careful consideration of scattering values. It is important to recognise that reverberation encountered in the open amphitheatre is not a diffuse field, but primarily comprises a series of non-diffuse lateral reflections off tier risers. Reverberation times are shortest at low frequencies as the long wavelengths are diffracted to the greatest degree by the tier risers, resulting in greater effective scattering at these frequencies. In CATT-Acoustic, this diffraction can be approximated by enabling automatic edge scattering on the tier riser planes. With increasing frequency up to 2 kHz, reflections become more specular and less scattered as wavelengths become smaller relative to the tier heights. Above 2 kHz, reverberation times reduce with increasing frequency as air absorption becomes more significant.

We began by using the ‘Estimate’ function within CATT-Acoustic to estimate scattering values based on a surface roughness depth of 100 mm. This value was selected to account for scattering provided by the tier nosings, gaps and cracks of damaged stonework, and intermediate curvature of the tiers between facet divisions. From this basis, scattering values were adjusted to match the calculated results as closely as possible to the site-measured results.

3.2 Modelling with audience present

The theatre is cited to have a capacity of 13,000 to 14,000 people [5]. Based on the lengths of the tiers (excluding gangways), this corresponds to an average seat spacing of approximately 470 to 500 mm, or approximately 0.36 to 0.39 m^2 per person. While this could be described as ‘cosy’, it is not excessively cramped by modern standards.

We have assumed absorption coefficients for a seated audience based on standard data for an audience on acoustically hard seating. Inherently, the introduction of a seated audience will increase acoustic scattering, particularly at high frequencies. We have estimated scattering values for a seated audience assuming a surface roughness depth of approximately 900 mm.

3.3 Modelling with skene building present

To complete the picture of how the theatre may have sounded in its heyday, we have investigated the acoustic effect of inserting the skene building behind the stage. While the extent of the building footprint is evident from the remaining footings, the height of the skene building is not certain. For the broad purposes of this exercise, we have assumed a two-storey building with an eaves height approximately equal to the height of the stone archways to the side of the skene wall. Figure 9 shows a view of the CATT-Acoustic model with skene building. We ran the model both empty and with a full audience present.

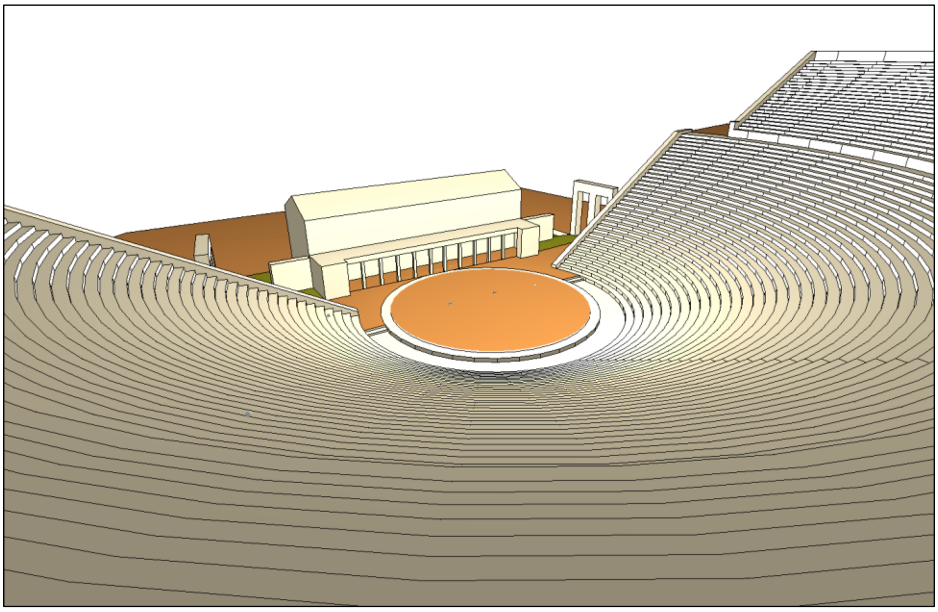

Figure 9 – View of skene building in CATT-Acoustic model

3.4 Calculation results

Figure 10 shows a comparison of calculated T30 reverberation times in the empty theatre and with a full audience, with and without the skene. These are averaged between source positions S1 and S2, and receiver positions R1 to R3. The error bars show the spread of results obtained as +/- 1 standard deviation from the arithmetic mean. Encouragingly, the spread of results obtained in the empty theatre model at mid and high frequencies is generally similar to that obtained from the on-site measurements.

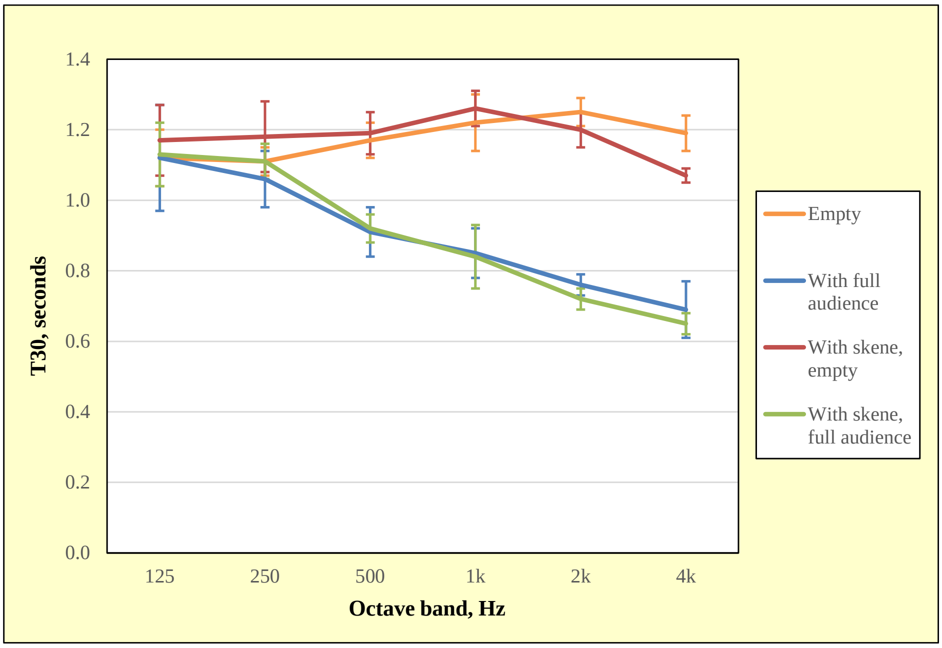

Figure 10 – Comparison of calculated T_{30} reverberation times in empty and full theatre, with and without skene building

The results indicate that the mid-frequency T_{30} reverberation time, T_{mid}, in the fully occupied theatre would be approximately 0.9 seconds, reducing further with increasing frequency. This reduction in reverberation time in comparison to the empty state is primarily due to the reduction in non-diffuse lateral reflections from tier risers. This is due in part to the increased absorption provided by audience members, but also the increased acoustic scattering.

The presence of the skene building may have resulted in a slight increase in low-frequency reverberation times, more significantly in the empty theatre. At high frequencies, the predominance of non-diffuse lateral reflections in the absence of the skene building results in the apparent reduction in reverberation time when the skene is introduced. This effect is commonly observed in extremely non-diffuse acoustic models with near-total absorption in one axis but a high degree of reflection in another, and is another reason for not relying on RT for assessing the acoustics of this type of space.

Will the presence of an audience have affected sound from the stage? As discussed earlier, the relative level of lateral reflected sound is substantially lower than that of the direct sound and the primary source of early reflections is the stage floor, which would not change with the audience present. The secondary early reflections, from the tier risers directly behind the receiver, would be scattered and absorbed by the audience and this would slightly reduce the overall sound level.

Sound strength G could not be measured directly on site with the balloon burst method, so we have compared calculated results obtained from the CATT-Acoustic model. Figure 11 shows a comparison of calculated sound strength G, as a logarithmical average of octave band results from 250 Hz to 2 kHz, from source positions S1 and S2 to receiver positions R1 to R3 in the empty and occupied conditions, with and without a skene.

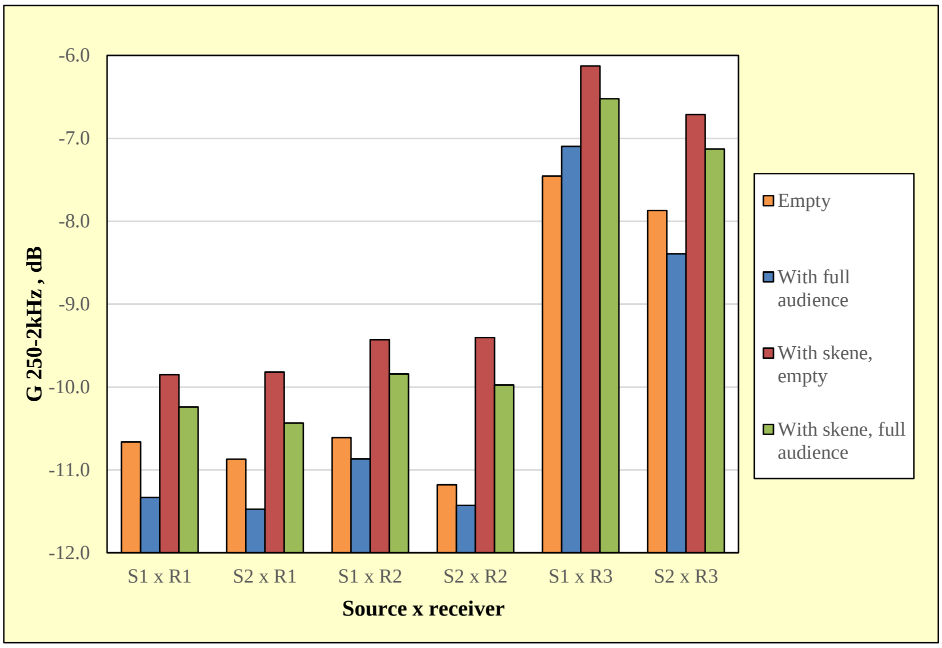

Figure 11 – Comparison of calculated sound strength G in empty and full theatre with and without skene building

The results show relatively little difference in G between the empty and fully occupied states without the skene. The variation in all cases is less than 1 dB, which is unlikely to be significant in practice.

The differences in G between receiver positions are primarily driven by distance from the source, since G is expressed with reference to the free-field level at a fixed distance of 10 metres from the source. When compared to calculated free-field levels at these positions, sound levels at receivers R1 to R3 are between 3.9 and 4.4 dB higher than equivalent free-field levels. This is a very modest degree of reinforcement, suggesting that the contribution of reflected sound from tier risers is relatively minor compared to reflections from the orchestra floor, which we expect to account for approximately 3 dB of the improvement over free-field propagation. There is otherwise very little variation in the strength of reinforcing reflected sound with distance from the stage.

Unsurprisingly, the results show an increase in G from the mid-stage sources with the introduction of the skene building. In most cases, this increase is around 1.0 – 1.5 dB. However, with reflections off the skene building from mid-stage sources arriving at receivers more than 80 ms after the direct sound, as shown in Figure 12, centre time (Ts) is increased, although without the unrepresentative "step function" increase that we would see if we were relying on C_{80}. Figure 13 compares calculated Ts results averaged from octave band results between 250 Hz and 2 kHz in the empty and occupied theatre with and without skene. The increase in Ts is most pronounced at position R1 on the centreline, where acoustic reflections off the skene building are strongest.

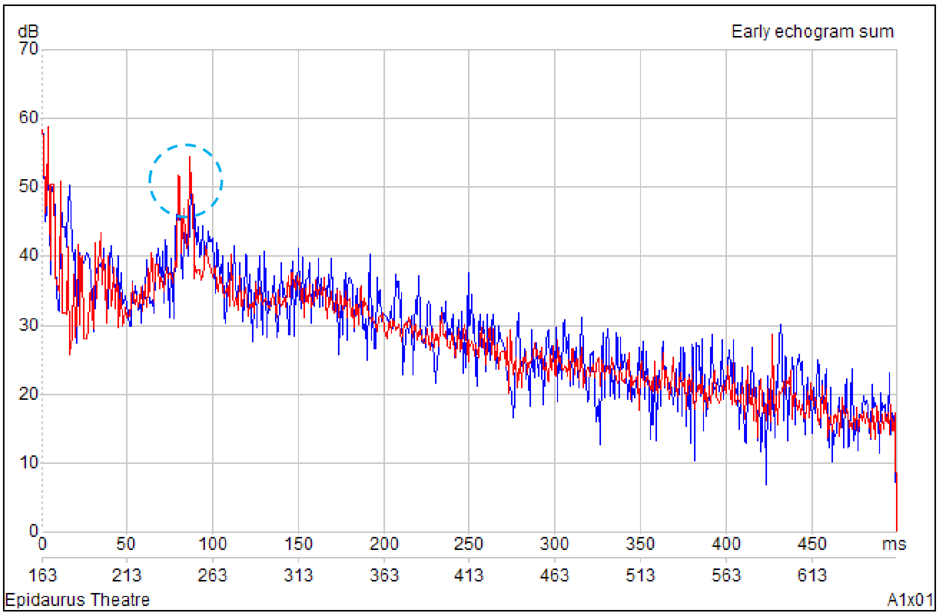

Figure 12 – Echogram of calculated decay at R1 in empty theatre with skene – 80 ms and 85 ms reflections off skene building circled

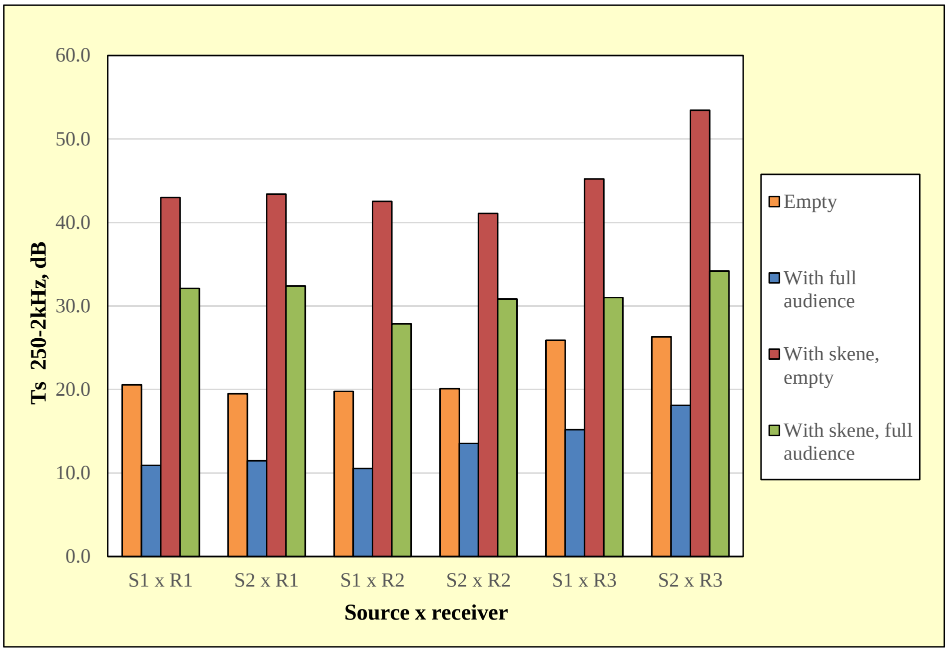

Figure 13 – Comparison of calculated centre time Ts in empty and full theatre with and without skene building

While this late reflection is particularly strong for mid-stage omnidirectional sources, in practice the effect is likely to be less pronounced. Human talkers are not omnidirectional and generally where actors have their back to the skene to address the audience, the level of sound projected upstage towards the skene will be reduced. Also, where actors are positioned upstage of centre, the path difference and hence the delay of the reflected sound will be reduced. Typically in ancient Greek theatre, the principal actors would perform directly in front of the skene, with the chorus occupying the orchestra downstage.

4 CONCLUSIONS

Were our findings in line with the popular understanding of acoustics at this and other amphitheatres?

Using directional impulse measurements taken on the site at Epidaurus, we identified primary reflection paths from sources on the orchestra to selected receiver positions. Our acoustic computer model of the amphitheatre reliably reproduced the results measured on site in the empty space.

Directional analysis of impulse measurements shows that early reflected sound reaching audience members downstage of the orchestra is primarily from the orchestra floor and secondarily from tier risers immediately behind the listener. The degree of reinforcement that these reflections provide over free-field levels is very modest. ‘Reverberation’ in the empty amphitheatre is due to lateral reflections off curved risers and is much weaker in level than would be found in an enclosed space. Centre times are therefore very short and show relatively little variation with distance from the stage.

Predictably, the addition of a full audience reduces reverberation and centre time at mid and high frequencies but has relatively little effect on sound strength. While reflections off tier risers behind listeners are reduced when occupied by audience, early reflections off the orchestra floor remain unchanged. The addition of the skene building yields a more significant increase in sound strength from sources in the orchestra, particularly for audience close to the centreline, but results in a longer centre time for orchestra sources due to late reflections off the skene façade. We know that principal actors would typically perform directly in front of the skene rather than from the orchestra, which was occupied by the chorus. Therefore late reflections are likely to have been less problematic in performance.

Circular amphitheatres such as Epidaurus primarily provide good sightlines for the audience. As such, listeners enjoy generally unimpeded direct sound from the stage, with supporting early reflections off the stage floor and skene. We conclude that the presence of an audience is unlikely to have significantly impacted the clarity of speech from stage. However, it is likely that even a settled and attentive audience would create higher ambient noise levels than an empty amphitheatre. This may well have resulted in issues with intelligibility in the rear rows both of the original theatre built in the 4th century BC and in the later extension.

5 REFERENCES

1. Picture credit: Carole Raddato, Creative Commons Licence CC BY-SA 2.0

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