SOME FACTS ABOUT THE ACOUSTICS OF THE THEATRE OF EPIDAURUS

The good acoustics of Epidaurus ancient theatre are famous worldwide. Most visitors test this by listening to speech and sounds produced in the "orchestra" whilst moving on the seating rows of the theatre's cavea ("koilon"), even reaching the more distant rows, nearly 60 meters from the orchestra.
But, what do we mean by "good acoustics"? Is this a subjective impression, or can it be objectively assessed? *If it is so, how do we go about measuring the acoustic properties of this theatre* and how does it compare to modern buildings, theatres or spaces where large audiences can enjoy theatre or music performances? What are *the exact characteristics of this theatre contributing to these renowned "good acoustics"?* Finally, *how did the ancient designers and builders achieve such results* that we still admire after more than 2000 years? We shall attempt to answer these questions by summarising the recent scientific results noting that for many years the reasons of the good acoustics of Epidaurus were a subject of various speculations. However, there is now sufficient information which was published in scientific journals and conferences, especially during the first international conference on the Acoustics of Ancient Theatres held during September 2011 in Patras, Greece. This Conference was co-organised by the Hellenic Institute of Acoustics and the European Acoustics Association.

What do we mean by saying that the theatre has "good acoustics"?
Noting that the Epidaurus theatre was mainly used and designed for staging theatrical performances, "good acoustics" first indicates that listeners can perceive with perfect intelligibility what the actors and the chorus are saying or singing when they perform on the stage building or in the orchestra, in front of it. Secondly, the term indicates that the quality of the received voices and sounds retains all their natural characteristics. We must note that during the ancient theatrical performances, the actors were performing wearing head-enclosing theatrical masks from the raised stage of a currently non-existent backstage building, whilst the chorus was performing from the orchestra floor we see today. These differences between the theatre's ancient and current form and use are responsible for subtle changes in the observed acoustic properties today. Furthermore, during modern performances of ancient drama, some backstage theatrical scenery is employed which assists the actor's voices and functions acoustically up to a degree in a comparable fashion to the ancient backstage structure.
The Epidaurus theatre has excellent acoustics with perfect *speech intelligibility* at all listening positions which cover the theatre's audience capacity of up to 14500 people. Speech intelligibility can be measured accurately and reliably with modern techniques, as will be explained in the following section. With perfect speech intelligibility assigned a mark of 100%, the measured results for Epidaurus have values between 85% and 95% for all listener positions even at such large distances as 60 meters from the speaker, when the direct sound power of the speaker's voice diminishes. Today, in order to approach such exceptional acoustic coverage for large audiences and long source-listener distances, e.g. in open-air concerts or speeches or in large auditoria, we rely solely on electroacoustic sound

systems that are expensive, need many man-hours of labour work to be properly set-up and consume many kilowatts of electric power. Instead, this ancient theatre remains acoustically functional for more than 2000 years and is ecological both in terms of fully utilising the sound energy of the human speakers and also at being in perfect harmony with its environment.

In addition to preserving speech intelligibility, *the quality of the voice* received by the listener remains natural and rich in expressive nuances, even at the furthest positions. The term "voice quality" will be explained in more detail in the following sections. The theatre's acoustics are less appropriate for reproducing music, typically this being assessed via the "reverberation time" parameter. If reverberation time was measured for this theatre (which is not exactly appropriate) this parameter has approximately value of 1 second, being "dry" for such sounds although today this may be corrected via electronic means and electroacoustic reinforcement. At the absence of such devices, the ancient Greeks deployed roofed theatres ("odeia") with higher reverberation appropriate for such music performing functions.

The open theatre of Epidaurus remains the perfect example of a large space that is acoustically optimally tuned to support the performances of ancient drama.

How do we measure and analyse the acoustic properties of the theatre?

During the past decades, the acoustics of Epidaurus have been properly studied *via acoustic measurements and computer model analysis*. Modern measurements rely on acoustically exciting the theatre via specific, controllable test signals (noise bursts, sweeping tones) either generated from loudspeakers having specific radiation properties, or produced from explosive sources such as bursting balloons, shotguns, firecrackers, etc. These test signals are recorded by microphones located at specified audience positions and then analysed via computer software to derive acoustic parameters, including the standardised measure of Speech Transmission Index and Rapid Speech Transmission Index, which rates the intelligibility of speech when received from the given source position. These acoustic parameters correlate well to the subjective evaluations of most listeners if they were seating at the same positions as the microphones were mounted. Given that human listeners rely on their two ears to receive and evaluate sounds, lately such measurements of the Epidaurus theatre used dummy head mannequins with in-built in-ear microphones to assess better the binaural and spatial properties and parameters of the theatre's acoustic response. The results of these studies fully confirm via objective measures the theatre's good acoustics and its amazing performance with respect to speech intelligibility and voice quality for all the audience positions. Significantly, given that the acoustics of spaces may change with the presence of an audience, very recent acoustic measurements obtained during a scheduled ancient drama performance with audience present during a festival, have confirmed that speech intelligibility remained exceptional.

What are the exact characteristics of this theatre that contribute to those renowned "good acoustics"?

At first, there are some obvious factors that are responsible for these "good acoustics". First, unlike most other ancient theatres, the theatre of Epidaurus has been preserved in an extremely good state, practically having intact all the tiers and structure of the koilon and with only the stage building structure missing. Secondly, it is well-isolated from the pollution created by the noisy modern activities and hence the level of background noise is

low, typically only due to the activity and voices of the modern visitors or spectators. These factors allow the acoustic functionality of the building to remain close to its original conception, thousands years ago. The design of the koilon, semi-enclosing the stage (orchestra) and also having 3 centres of curvatures, also improves audience visual and acoustic proximity to the sources on the stage, especially for the more problematic side seating positions. Nevertheless, there are additional mechanisms that are responsible for the theatre's acoustic properties.

The exact acoustic mechanisms for such impressive results had remained until recently a topic of open debate and speculations. The experts were unable to clearly identify the acoustic mechanisms and mostly referred to the beneficial effects of reflections generated by the theatre's geometric shape or even to temperature-related air currents assisting the radiation of sounds from the stage and orchestra to the upper area of the cavea. Some tourist guides still refer to mysterious "acoustic centres" on the orchestra often erroneously associating this to the central marble slab and even to other speculative factors. The recent results allow now the following summarised conclusions.

It is now clear, that from any sound produced in the orchestra, the geometric shape of the theatre generates reflected and scattered sound energy which comes from the orchestra floor and the limestone surfaces at the back of seat rows around the listener position. The main bulk of this reflected sound energy arrives at the listener's ears shortly (within 40 milliseconds) after the direct signal and as far as the listeners' brain is concerned, this is sound also coming from the direction of the source at the stage. In this way, the voice is perceived to be significantly amplified and this increase in voice level is sufficient to ensure good speech intelligibility.

The exact width of the seating rows (0,746 m) and the height of the seat backs (0,367m), as well as the cavea slope ($26,2^0$ for the lower rows and $26,5^0$ for the upper rows), result to fine tuning of in-phase and out-of-phase combinations of these direct and reflected sounds, so at all positions, frequencies useful for speech perception (from 500 Hz to 2 KHz) are amplified whereas any attenuations affect relatively insignificant voice spectral regions (around 200 Hz). This property ensures the preservation of the "voice quality" at all listening positions which is complementary to the previously discussed improvement in perceived voice level. It can be observed in an exaggerated way when the modern visitors clap their hands at the orchestra and by hearing the response from multiple in-phase and out-phase reflections from the limestone cavea surfaces which create a distinct metallic-sounding effect. In fact, this "return" of the theatre's acoustic response affects mainly the listener at the orchestra and the performing actors. Nevertheless, this "return" acoustic response is also diffuse and fast-decaying so that it is not detrimental to speech produced on the stage. Furthermore, from contemporary actors' comments, it is deduced that this distinct acoustic signature changes when the theatre is filled with audience.

How did the ancient engineers and builders achieve such results?

The design and shape of the theatre of Epidaurus was apparently the result of a lengthy evolutionary process, which had assimilated many social, political, technical and aesthetic-artistic factors. The designers had to meet requirements related to perfect sight lines, and uniformly perfect hearing by the large audience. With respect to acoustic design, there is a significant gap in the available historic sources, but from the second-hand evidence given by the Roman architect Vitruvius, it is likely that the ancient architects considered the

beneficial or detrimental effect of reflected sounds on the theatre's surfaces. However, it is unknown whereas exact conscious rules were applied into the theatre's design with respect to the critical dimensions of benches, slope, radius, etc. which were previously shown to contribute to the Epidaurus theatre's good acoustics, or if instead the architects followed empirical choices. Irrespective of the design process, the end results remain excellent even when judged by today's highest standards and sophisticated scientific procedures.

Note also that the theatre is part of a complex of buildings situated in the nearby valley, constituting the famous ancient sanctuary of Asclepius, the god of health, medicine and healing. The acoustic clarity of voices and sounds during the theatrical acts was also considered as important element of this healing process; hence it appears that the location of the theatre and the valley were carefully chosen in order to protect the theatre space from extraneous noise and provide ideal atmospheric conditions for voice transmission. Even today, the area remains largely free of such interferences from modern day activities.

In conclusion

The acoustics of the theatre of Epidaurus were perfectly tuned for the performance of ancient drama and were result of an evolutionary design process. The measured results are excellent and well understood by using modern methods so there are not any unknown or metaphysical factors to the theatre's acoustic properties. We must appreciate that this ancient theatre presents the finest earliest example of how acoustic design can support and enhance speech communication over large public audiences. Such an achievement was possibly crucial for the wide acceptance of the theatrical, music and other performance-based arts by the ancient Greek society. Via the geographical spread of these theatres and their continuous evolution through the Roman era up to modern times these art forms have been established as an indispensable part of the western cultural heritage and became a timeless and universal constituent of our civilisation.

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