The acoustic model of the Greek theatre

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Summary

The evolution of Graeco-Roman theatre, during its thousand years in existence, is interpreted as a two-sided problem concerning geometric acoustics and visual geometry, and, beyond that, as the first step in a more general acoustic model, which encompasses all theatre designs whose primary criteria is capacity.

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I. INTRODUCTION

Over the past few years, there has been a renewed interest in the acoustics of ancient theatres. In general, articles on the subject are based on measurements of the sound field carried out in major theatres, such as the ones in Epidaurus and Dodona [1], Aphrodisias and Aspendos [2].

Sometimes, it is simply a matter of becoming better acquainted with the auditory qualities of these places, where performances are still regularly put on. The problem is that these measurements are often taken when there is no audience present, even though an audience significantly modifies the acoustics of these stone structures. These measurements are also often a pretext to assess simulation programs based on ray tracing [3, 4], which does, or does not, take into account diffuse reflection. It is therefore difficult to deduce the original properties of these theatres which are now in ruins. Indeed, they are sometimes in a remarkable state of preservation but the marble surfaces have disappeared and the stones themselves are heavily eroded, which obviously affects the specular and diffuse components of the reflected sound.

In our opinion, too much attention is paid to secondary effects as a result of these works (multiple reflections between the stage and the tiers, or between the opposite sides of the tiers), which fade significantly in the presence of an audience. They do not, in any way, explain the beginnings or the function of these theatres, and they scarcely take the motivations of their architects into account, and, finally, cannot direct us in our own architectural projects.

Over the past fifty years, researchers in theatre acoustics have expressed a certain reserve as regards design-oriented architectural culture, although they alone are in a position to justify the measurements and analyses, in order to help create new spaces. Instead, there has been an attempt to propose a series of parameters that will hopefully provide complete knowledge of the sound field and its perception. And yet, this intention is somewhat fanciful if we examine the acoustics of ancient theatres. There is a high level of clarity, but the sound is much less reinforced than in modern theatres equipped with a roof. The level of reverberation in Epidaurus is very low (where all stage devices have disappeared [1]), and more than notable in Aspendos (where the *scaenae frons*, which completely closes the walls of this Roman theatre, is almost intact [2]). However, it would be rather anachronistic to highlight such a parameter in these places where measurements were taken when they were empty: there can scarcely be any reverberation when an audience is present since these places were not designed with such an intention in mind. If we were to look for the premises at that time for what we would call the "reverberating model", we would do better to study the Roman basilicas, the ancestors of Christian churches where, perhaps for the first time, musical works were composed in Europe especially with reverberation in mind.

And yet, there appears to be no doubt that ancient theatres belong to a radically distinct acoustic model, which must be examined according to its own constructive and functional logic, with purely geometric tools. We must therefore return to the works of F. Canac [5], which are the most complete to date. Unfortunately, the progress made in the domain of measuring acoustics does not teach us anything new, since it was not applied for the same reason as the one in question here. On the other hand, we can attempt, as we are going to do, to exceed the most debatable limitation of F. Canac’s work, which was based on an "ideal" theatre (i.e. Epidaurus) and underestimated the importance of the historical evolution.

Historical models can only be properly understood through their evolution. They reveal the thoughts of the architects involved, their desire to do better and their own limitations. In short, what was at stake at the time, and what is still at stake today.

II. THE EVOLUTION OF THE GRAECO-ROMAN THEATRE

The Greek theatre and its Roman avatar have been used for nearly a thousand years: since the time of Pericles (or slightly before) up until the fifth century A.D., when, under Christian influence, and then owing to the fall of the western empire, all places that staged performances were gradually abandoned. We shall divide the study into four periods in a conventional manner: archaic, classical, Hellenistic and Roman. We should immediately point out that this list, as regards the evolution of the theatre, is constantly behind in relation to the correct historical division on which it is based.

We do not have the slightest trace that is truly conclusive concerning the archaic era, which we cannot reasonably trace back very far, and certainly not the Cretian or Mycenaean eras, since public places tended to adopt a rectangular form, the most common form among ancient civilisations (in America or in China, for instance). We can only accept the hypotheses of the ancient authors who generally claimed that theatre was created on the sides of the Acropolis in Athens, undoubtedly at the time of Peisistratos (around 530 B.C.), as an extension of the worship of Dionysus [6]. These beginnings would explain the double specificity of the theatre of Dionysus, and all its subsequent equivalents: tiers like a truncated cone on the side of the hill (the *koilon*) and a double stage, composed of a circular space (the *orchestra*) and the actual stage itself, situated in front of a simple curtain (the *skene*) that later became the *scaenae frons*.

The *proskenion* was then elevated above the orchestra, to provide better visibility. This narrow stage, where the original priest was replaced by two then three actors (never more in Greek tragedies) was opposite the free space of the orchestra, which housed the chorus and their leader, the coryphaeus. All the theatres from the classical period were modified during the following era and their stage structures, which were made out of wood, disappeared. Despite these unknown factors, two developments clearly characterise the Hellenistic theatre: new rows of tiers were added to the koilon, and the proskenion was raised much higher, up to more than three metres above the orchestra.

As for the Romans, the construction of stone theatres did not begin until the final years of the republic, and the main examples that still exist, date from the first to the third century A.D. These theatres were not built on a hillside, and formed a closed ensemble which only lacked a roof.

III. ABSTRACTION OF A TYPICAL THEATRE

We are now going base our study on a typical theatre. We shall try to imagine how people thought at the time, and if they actually introduced the notion of acoustics, while taking into account that acoustics could not be expressed in the same way as they are today, and taking care not to project anachronous knowledge onto these old ideas.

At the start, there was indeed the idea of forming the audience in a circle around the action, and to spread it over tiers. This seems obvious, for simple visual reasons, and yet, there is nothing similar in any other ancient civilisation.

In a recent book [7], Paul Veyne speaks of a “new idea”, strictly Greek, relating to an “aristocratic ideal which was extended to an entire self-proclaimed civic body, peasants and townspeople”, and he adds the following observation: “As from the time of the Iliad, there was no more despotism but, instead, there were "kings", who were more or less kings, and one of whom, Achilles, was able to send Agamemnon packing, who was, however, the most regal of all. In the event of a major problem, the army would form a circle with a free collective and impersonal space in the middle of this warlike community”.

The structure that was built much later, on the sides of the Acropolis, was therefore the consequence of this extended aristocratic ideal, and it is actually to a comparable phenomenon that we owe the reappearance of the same “circular model” of theatre during the Renaissance, after its thousand-year absence. Was it not this intention that governed the birth of Italian opera? Everywhere in Europe where the aristocratic ideal prevailed, horseshoe-shaped then fan-shaped theatres were constructed, while the bourgeois taste for English or German concerts often favoured rectangular rooms.

For the Greeks and Romans, the theatre was a public place of primary importance, and the religious or profane performances that took place there were the very stamp of civilisation, the pride of the city: in 418 B.C., eight years after the sacking of Rome by the Goths, the citizens still demanded performances and games, as proof of a return to normal [7]. The theatres always attracted an unbelievable crowd, and this is why they were built in gigantic proportions. They were places that were only intended for massive audiences. Their shape corresponded to the necessity of enabling thousands of people to see a small stage ("only" 5000 in Priene [8], but up to 25,000 in Ephesus [9]). This is what defined the circular model and its original acoustics, with its advantages and limitations. In the beginning, the idea was that what could be seen well could be heard well: by clearing the view, the way was clear for direct sound. For this dual purpose, very steep tiers are required and, better still, the slope should increase with the distance from the stage. In the biggest theatres, the koilon is divided into two concentric areas (even three), by a circular passage (the *diazoma*) above which the slope may be increased.

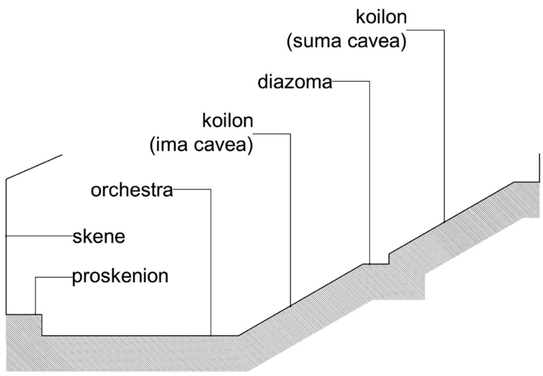

Fig. 1: Longitudinal cross-section of the theatre, with a diazoma dividing the tiers.

The important parameter is the angle of incidence which the radius of the direct sound creates with the line of the heads of the audience. The greater this is, the clearer the view and the better perceived the direct sound. However, sound does not behave in quite the same way as light: for glancing incidences, there is a good chance that the wave fronts will be partially absorbed and deformed by the audience located at the front, and that there will be a high level of variation in this absorption according to the frequency. It is here that measurements should be carried out with stone tiers; this should modify the results obtained in modern theatres. Although such measurements would be difficult to carry out *in situ,* with an audience, they would indeed be far more useful than the measurements taken in empty theatres.

However, the acoustics of Greek theatre does not only depend on the truncated cone-like arrangement of the audience and the free deployment of the resulting direct sound: its highly particular form, resulting from the worship of Dionysus, provides it with two essential sources of reinforcement. As mentioned above, the stage in Greek theatre is narrow: 2.4 metres in Epidaurus, less than 3 metres in Priene, Pergamon or Syracuse, and 3.3 metres in the Athenian theatre of Dionysus in Hellenistic times. This allows an almost immediate reflection off the *scaenae frons*, which reinforces the sound level without affecting the clarity of speech. It is very instructive to compare these results with what happened in Rome, where there could be far more actors on stage, and where the proskenion was subsequently a lot deeper. In all the cases that we have studied [10], the reflection delay time did, however, remain under the value of 50 milliseconds, which is currently accepted as the limit for the intelligibility of speech. Thus, in the extreme case of the theatre at Ephesus, where the stage is 7.8 metres deep, the maximum delay time, in relation to the first tiers, produced by an actor situated at the edge of the proskenion, is limited to 46 milliseconds. In this case, it is sufficient to increase the depth to 9 metres to exceed the maximum value. This clearly indicates that the Roman architects had realised this limit and consequently controlled the geometry of their theatres.

The second source of reinforcement is provided by the reflective surface of the orchestra, which would seem to be the most original idea in Greek theatre: to distance the audience slightly from the stage, to provide a primary second reflection with a very short delay time (the delay times are always negligible here). However, there are other examples of this type, such as Chinese theatre, where the stage lies over a stretch of water, which distances the audience while reflecting the sound [11].

In Greek theatre, the result of this highly noteworthy configuration is that the entire audience is in the reflected field, i.e. all the sound reflected off the stage and the orchestra is always greater than the direct component. Therefore, everyone can hear mainly thanks to the architecture. In fact, it is the simplest and most economical way of creating this effect. Of course, the ambient sound must be very low for it to work, but the result is amazing: the audience can see very well and hear very distinctly, because a highly reduced number of strong reflections are added to the direct sound. It is an elegant and fragile solution that should be neither over- or underestimated: suffice it to consider the numerous geometrically incorrect modern imitations in order to perceive the real contribution of these modest reflections to correctly sloping tiers.

IV. USING THE "RADIT2D" PROGRAM

In 2002, we began developing a computer program to assist acoustic design, aimed at architecture students and professionals [12]. It allows us to take a cross-section and study the variations in direct sound and primary reflections according to the layout of the enclosed space studied. Its main characteristic is that all the calculations are made in an analytical manner (contributions in decibels, elimination of hidden parts, sound level maps and polar diagrams), so that it is truly interactive and numerous configurations can be rapidly tested (position of the source and the receiver, position and orientation of the various reflective surfaces, absorption factors).

In this case, the "Radit2d" program allowed us to compare numerous cases of theatres by varying the position of the source on the proskenion and the orchestra [10].

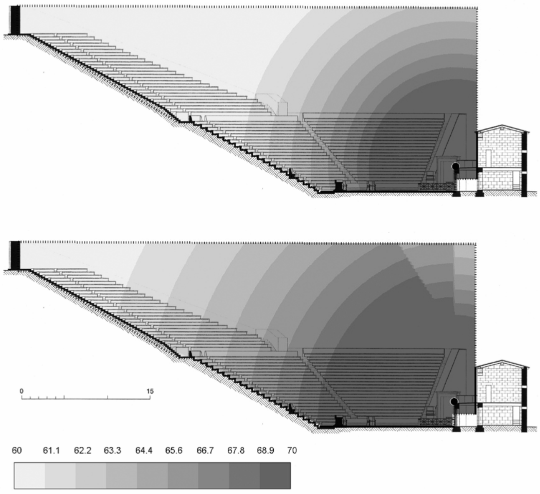

Fig. 2: Only direct sound (above), then added to the reflections off the orchestra and off the skene (below); transparent program map of a cross-section of the theatre in Priene (diagram hereafter [8]).

In the theatre at Priene, we can thus check whether someone in the first row would already benefit from a reflected level of sound (Lp^r = 66.8 dB) higher than the direct level (Lp^d = 65 dB), even if we only take into account the first reflections off the orchestra and the *scaenae frons* (these two surfaces are considered to be perfectly reflective). This would have always been the case in ancient theatres, with the audience receiving at least two reflections.

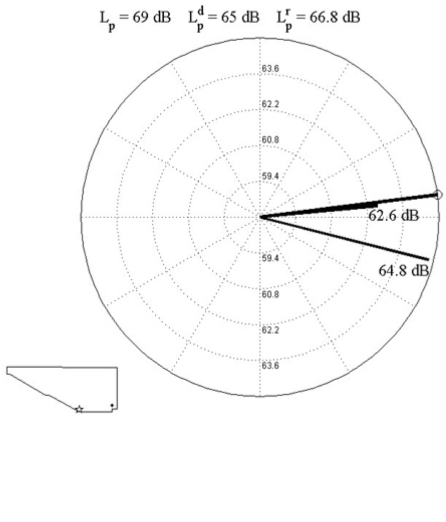

Fig. 3: Polar diagram from the program, for someone sitting in the first row of the theatre in Priene, with a source on the edge of the proskenion; the reflections off the skene (62.6 dB) and off the orchestra (64.8 dB) give a higher level of reflection (66.8 dB) than the level of direct sound (65 dB).

V. EVOLUTIONS IN THE TYPICAL THEATRE

We shall now endeavour to explain how the typical theatre we have just described was able to evolve, despite all the uncertainties owing to the disappearance of the surfaces and wooden structures from the sites, and the impossibility, in most cases, of clearly distinguishing the different phases of transformation. Here, we shall refer to three examples of Hellenistic theatres (Athens [5], Epidaurus [13] and Priene [8]) and three Roman ones (Orange [5], Aspendos [14] and Ephesus [14]), which are among the most representative and the best known (see table I).

In Hellenistic times, the main problem was capacity: some theatres became very large, through the addition of new tiers, and it became difficult to preserve the visual and acoustic qualities. All the more so owing to the limitation of building on a hillside. Therefore, in the theatres of Athens and Priene, the slope of the tiers is constant, and the angle of incidence of the direct sound may be critical for the last few tiers (only 7° in Athens, for a constant slope of 21° for the tiers). There has often been reference to the actors using masks to project their voices, but this has never been proved [13]. It seems that the solution generally adopted was to significantly raise the proskenion: in Priene (only 2.7 m., but with steeply sloping tiers at 29°) and in Epidaurus (3.8 m.), the angle of incidence was always above 10°. Of course, the stage can only be raised so far owing to the necessity of maintaining the visibility of the first rows of the koilon, which were reserved for notables.

But there is another unfavourable result, concerning the acoustics only: the higher the proskenion, the lower the angle of incidence of the reflection off the orchestra to the audience. For the first time, we are faced with a contradiction between the interests of sound and vision. In Priene and Athens, the sound reflected off the orchestra reaches the back rows with an incidence lower than 3°, and is therefore significantly absorbed by the audience sitting in the lower rows. On the other hand, in Epidaurus, despite the greater height of the proskenion, but thanks to the slight increase in the slope of the tiers above the diazoma, the two angles of incidence are better (more than 12° for the direct, and, in particular, more than 4° for the reflected, at the level of the last tiers): this is maybe enough to explain the excellent reputation of the acoustics in this theatre.

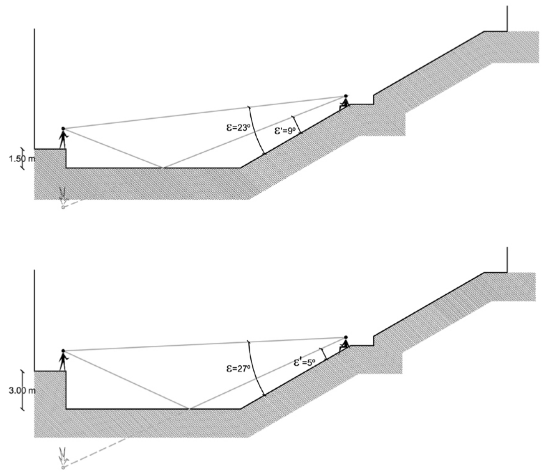

Fig. 4: If we raise the proskenion, the angle ε of incidence of the direct sound to the audience increases, but the angle ε' of incidence of the reflected sound decreases.

When people wanted to rebuild the *scaenae frons* in Epidaurus for modern performances (the original having completely disappeared), they soon realised that this wall was detrimental to the acoustics [1]. Undoubtedly, the reason was that the actors wanted to play too far forward over the orchestra, and therefore too far from this wall, thus causing an echo. At the time, this would not have happened, because the actors certainly stayed on the proskenion, and the coryphaeus was in a very particular location: the stage behind him was so high, that his voice was no longer reflecting off the back wall, but off a new wall, the foot of the proskenion, just behind him, 3.8 metres high. Consequently, there was a complete split between the two stage spaces: the proskenion, placed up high, which had almost lost the reflection off the orchestra (but maybe gained a geometrically well-oriented roof, and just as efficient, since it was not very high and produced a reflection not subject to the glancing incidence), and the orchestra, less favourable acoustically, though protected from the unfavourable echo, which could have bounced off the s*caenae frons,* owing to the fact that it was tucked away (which is what undoubtedly happened in less well-controlled modern performances).

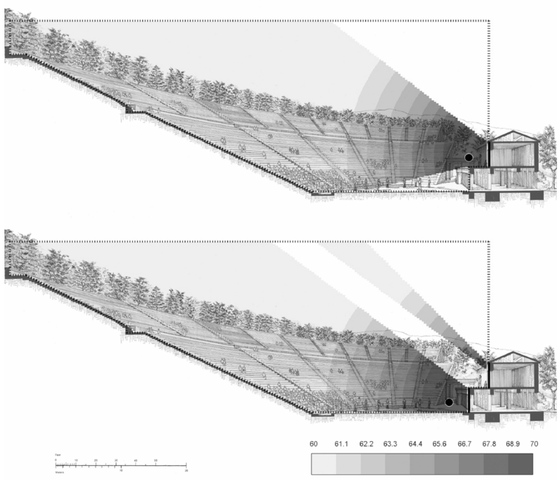

Fig. 5: Source on the proskenion in Epidaurus (above), then on the orchestra (below), where we see that that the reflection off the skene does not reach the audience; transparent program map of a cross-section of the theatre in Epidaurus (diagram hereafter [5]).

This is what could have happened during the Hellenistic period. In any case, the problem must have been fairly acute since the Romans, far from their reputation as simple imitators in this domain (although illogical, it was claimed that the orchestra lost its acoustic role in Roman times), invented an original solution, certainly well-thought-out and, indeed, very efficient.

Compared with their predecessors, they benefited from the advantage of no longer depending on the slope of a hill, since they elevated the koilon (the *cavea* in Latin) on horizontal ground. On the other hand, the places chosen to construct the theatres were less privileged, despite the revealing insistence of Vitruvius on this subject [15], and undoubtedly noisier. This would explain why these theatres were entirely enclosed, which provided a certain level of insulation. The Roman cavea is generally far more sloping than the Greek koilon, which is of course beneficial. Furthermore, the slope is always increased once, as in Orange (27° before the diazoma and 31° after) or in Aspendos (33° and 36°) and sometimes twice (as in Ephesus: 25°, 28° and 30°). On the other hand, the proskenion is lowered (its height is only 2 metres in Orange, 2.5 metres in Aspendos and 2.1 metres in Ephesus). It is also a lot deeper, but at the same time, it is sufficient for the performance of the actors', who do not have to go down into the orchestra, where the *scaenae frons* would undoubtedly produce a somewhat delayed echo.

As a result of these changes, the angles of incidence are much better, not only for the direct sound, of course, but especially for the sound reflected off the orchestra (they exceed 6° and 8°, respectively, for the last few rows in Orange and Aspendos). Even in Ephesus, where the slope of the tiers is more moderate, the angle of incidence of the reflection off the orchestra is much higher than 4° (i.e. as in Epidaurus), thanks to the two diazomas, which suddenly raise it each time it becomes too weak.

If there was any remaining doubt as to whether these improvements were a conscious choice, it is a Latin author who gives us the only clear confirmation that we know of concerning the acoustic role of the orchestra: Pliny points out that “holes or sand spread across the orchestra deflect the voice” (Pliny, Bk. 11, Chap. 32, quoted by F. Canac [5]). However, Vitruvius, the author of the only description of Greek and Roman theatres we know of, does not make any mention of this, and, furthermore, defends tiers with no change in the slope [15]. But the main sources of Vitruvius are Greek, and perhaps we would be right in supposing that between his generation and that of Pliny, i.e. right at the beginning of our time and the Roman Empire, greater attention was paid to the study of sound reflection, in parallel with the new architectural creations in stone.

On the other hand, the one thing the Romans clearly overlooked was acoustic reinforcement that a roof over the stage could have provided: it was placed too high up and, even if it had been placed correctly (which the virtual reconstitutions of the theatre in Aspendos [14, 16] seem to contradict, for instance), it would have created significant delay times (up to 80 milliseconds, according to our calculations [10]), which was not the case in Hellenistic theatres, where the *scaenae frons* was lower (according to our estimations, a correctly placed roof at Priene would have caused limited delay times of about twenty milliseconds only).

Finally, there were the odeons. According to modern interpreters, an *odeon* was a small theatre built beside the big main theatre, reserved for musical events in general, but it was also a covered theatre. This was certainly the case owing to its small size and the building techniques of the time. Thus, the reconstitution of the odeon at Pompeii [17] shows us a complete theatre, in miniature, closed in a box showing a lateral cross-section of the tiers that join the *scaenae frons*, and whose walls and roof are decorated and fitted with windows and boxes, so that the acoustic properties of these surfaces should have been mainly diffuse.

As regards the odeon's design, there is nothing revolutionary about it: it is not a radical change, but the exact transcription of the general idea of theatres to another scale. As for the performances that took place there, it would appear that the Graeco-Roman world only had one visual and acoustic model, but it patiently optimised and adapted it to new circumstances, to all the changes that occurred in stage design from the original worship of Dionysus by the Athenians on the flanks of the Acropolis to the great pantomimes and "private concerts" which characterise late antiquity.

VI. THE CIRCULAR ACOUSTIC MODEL

In the Middle Ages, the theatres of old were completely ignored, and a completely new kind of performance developed in very different buildings, i.e. churches and cathedrals: polyphonic music. These spaces have a high level of reverberation and, from an acoustic point of view, they make no separation between the "stage" and the "audience"; hence the spatial and resonance effects that were unimaginable in ancient performances. It was therefore a radically different acoustic model that began to appear from the end of the late classical period, then in Byzantium, in the western monasteries and in the cathedrals of Rheims and Paris. We shall call it the "reverberating model" in order to distinguish it from the former, abandoned "circular model".

During the Renaissance, when this model came into fashion again, it had already been influenced by this reverberation to which music had adapted itself. But we must not exaggerate: there was a radical break between the modal music of the Middle Ages and the new tonal system according to which operas were composed. This break owes a lot to the change in acoustics: the new theatres owe more to ancient theatres than to churches and any innovations were the result of something completely new – the central perspective of the decor – and the compromises this imposed on a type of construction which was in fact well prepared for it, since ancient theatres already required a drastic separation between the auditorium and the stage (much more than in Elizabethan theatre, for instance). Suffice it to convert the semi-circle of the koilon into a sort of horseshoe (or, later, a fan) and to stop reflecting off the orchestra.

As regards this point, it is particularly instructive to examine a transitional work, Palladio's "Olympic Theatre" built for the town of Vicenza around 1580. In fact, it is a sort of odeon: the tiers are still in a semi-circle beneath a perfectly flat roof. The first change concerns the décor, which is a surprising trompe-l'œil; but the small orchestra is so tucked away that it no longer allows the sound to reflect off it to the audience. Undoubtedly, the architect, who truly wanted to create a classical-style work, was unaware of its acoustic value. In any case, and maybe despite himself, he created something new: he had converted the orchestra into an orchestra pit for the musicians (and hence the appearance of the "orchestra" in the modern sense of the term). On the other hand, we can verify that the reflection off the roof, which acts as a substitution, is relatively well controlled, since its delay time barely exceeds 50 milliseconds. However, our sense of hearing is not very sensitive to the vertical angle of incidence of sound, owing to the symmetry of the human head. Therefore, we can reasonably assume that the acoustics of this theatre are very similar to that of an odeon, and that this was the turning point between two forms of the same acoustic model: on the one hand, ancient theatres, and on the other hand, all the new expressions of the circular model, which almost monopolised high-capacity auditoriums until the middle of the twentieth century (theatres, concert halls, operas or conference rooms).

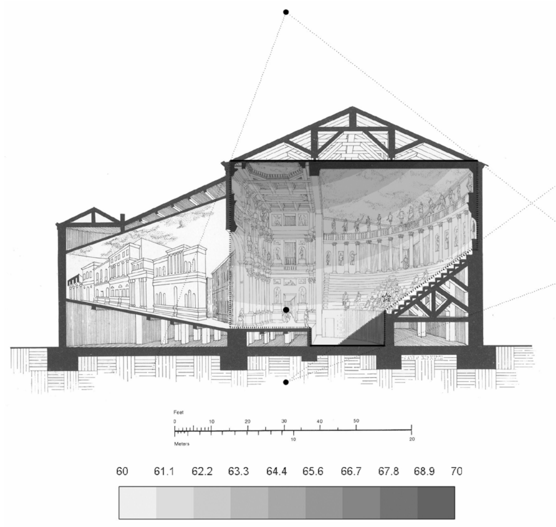

Fig. 6: Reflections off the roof and the orchestra pit in Palladio's theatre. From this position of the source, 2 metres away from the edge of the stage, the reflection off the orchestra does not even reach the first few rows, while the delay time of the reflection off the ceiling is exactly 50 milliseconds; transparent program map of a cross-section of the Olympic Theatre (diagram hereafter [6]).

However, in the nineteenth century, the third acoustic model of European theatre entered the scene. Parallelepipedal auditoriums were built on a purely functional basis, which have also sometimes been used for concerts over the centuries. Their acoustics are often surprisingly superior to constructions based on the Greek model. However, it was not until the second half of the twentieth century, after the pioneering work of Lothar Cremer (in relation to the Berlin

Philharmonic project), that the essential characteristic of this “rectangular model” was revealed: the presence of numerous lateral reflections, which, of course, were lacking in the circular model. The ultimate adventure of the Greek theatre was to attempt to generate these reflections, which increase the “feeling of envelopment”, through a system of terraces [16].

VII. CONCLUSIONS

In this study, we have attempted to think as architects, i.e. we asked ourselves why a certain geometric decision should be taken instead of another, because design interests us more than analysis. From this point of view, we began developing a computer program in 2002, “Radit2d” [12], whose interactive aspect helped us greatly in the comparison of cross-sections of the various theatres and various configuration options (stage, orchestra, tiers, possible roof, etc.).

This allowed us to suggest how theatres from High Antiquity to Hellenistic and Roman times, were able to evolve in what appears to us to be a fairly logical and reasoned manner. We believe that this work could help archaeologists interested in acoustics to describe their discoveries using the handful of parameters that have a decisive influence on the quality of hearing and, in particular, to present meticulous longitudinal cross-sections (for instance, we were unable to find a similar representation of the imposing theatre at Pergamon).

These are the parameters (height and width of the proskenion, height and slope of the possible roof, radius of the orchestra and, especially, the slope of the tiers) that still need to be optimised today, in the design of open-air theatres. Here, architects will find some elementary, though essential, advice.

However, we should not be misled by the great simplicity of these very ancient theatres: it was in these theatres that one of the three acoustic models of western theatre was created for the first time, and with great awareness and imagination. And it is this model that still attracts architects the most, and has the greatest bearing on the contemporary design of theatres and concert halls.

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[17] P. Ciancio Rossetto, G. Pisani Sartorio, “Teatri greci e romani. Alle origini del linguaggio rappresentato” (Greek and Roman theatres. At the origins of the represented language), published by Seat, Rome-Turin, 1994-6.

Table 1: Geometric data of the six theatres studied. Angle of incidence of the direct sound (ε) and the sound reflected off the orchestra (ε') to the audience, for a source situated on the edge of the proskenion, 1.6 metres high, and receivers distributed along the longitudinal cross-section of each of the theatres, 1 metre above the tiers. The theatre in Athens has a diazoma, though no alteration in the slope of the tiers, contrary to the theatres in Epidaurus, Orange and Aspendos. The theatre in Priene has no diazoma, while the one in Ephesus has two. The value "h" indicates the height of the source above the orchestra (height of the stage + 1.6 metres).

ATHENS (Slope of tiers: 21°; height of the proskenion: 2.50 m.)							
		first row	before 1st diazoma	after 1st diazoma	before 2nd diazoma	after 2nd diazoma	last row
angle ε	h =4.10 m	26.2°	14°	12.6°	8.8°	8°	7.1°
angle ε'	h =4.10 m	9.8°	5.3°	4.8°	3.4°	3.1°	2.7°

EPIDAURUS (Slope of tiers: 26°; 27°; height of the proskenion: 3.80 m.)					
		first row	before the diazoma	after the diazoma	last row
angle ε	h =5.40 m	32.5°	16.5°	16.6°	12.6°
angle ε'	h =5.40 m	8.9°	4.6°	5.5°	4.3°

PRIENE (Slope of tiers: 29°; height of the proskenion: 2.70 m.)					
		first row	before the diazoma	after the diazoma	last row
angle ε	h =4.30 m	39.8°	19.5°	17.9°	11.4°
angle ε'	h =4.30 m	9.2°	4.6°	4.2°	2.8°

ORANGE (Slope of tiers: 27.3°; 31°; height of the proskenion: 2.00 m.)					
		first row	before the diazoma	after the diazoma	last row
angle ε	h =3.60 m	33°	13°	14°	12.8°
angle ε'	h =3.60 m	13.8°	5.6°	6.9°	6.3°

ASPENDOS (Slope of tiers: 33°; 36°; height of the proskenion: 2.50 m.)					
		first row	before the diazoma	after the diazoma	last row
angle ε	h =4.10 m	36.9°	22.7°	22.1°	16.3°
angle ε'	h =4.10 m	16°	10°	11°	8.3°

EPHESUS (Slope of tiers: 25°; 28°; 30°; height of the proskenion: 2.10 m.)							
		first row	before 1st diazoma	after 1st diazoma	before 2nd diazoma	after 2nd diazoma	last row
angle ε	h =3.70 m	25.7°	15.8°	17.3°	12°	12.9°	10°
angle ε'	h =3.70 m	6°	3.7°	6.7°	4.7°	6.2°	4.8°

Fig. 1: Longitudinal cross-section of the theatre, with a diazoma dividing the tiers.

Fig. 2: Only direct sound (above), then added to the reflections off the orchestra and off the skene (below); transparent program map of a cross-section of the theatre in Priene (diagram hereafter [8]).

Fig. 3: Polar diagram from the program, for someone sitting in the first row of the theatre in Priene, with a source on the edge of the proskenion; the reflections off the skene (62.6 dB) and off the orchestra (64.8 dB) give a higher level of reflection (66.8 dB) than the level of direct sound (65 dB).

Fig. 4: If we raise the proskenion, the angle ε of incidence of the direct sound to the audience increases, but the angle ε' of incidence of the reflected sound decreases.

Fig. 5: Source on the proskenion in Epidaurus (above), then on the orchestra (below), where we see that that the reflection off the skene does not reach the audience; transparent program map of a cross-section of the theatre in Epidaurus (diagram hereafter [5]).

Fig. 6: Reflections off the roof and the orchestra pit in Palladio's theatre. From this position of the source, 2 metres away from the edge of the stage, the reflection off the orchestra does not even reach the first few rows, while the delay time of the reflection off the ceiling is exactly 50 milliseconds; transparent program map of a cross-section of the Olympic Theatre (diagram hereafter [6]).