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Roman Theatres and Revival of Their Acoustics in the ERATO Project

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Summary
The ERATO project was a three-year research project financed by the European Commission under the Fifth Framework INCO–MED Program (2003–2006). The acronym refers to the project title: Identification, Evaluation and Revival of the Acoustical Heritage of Ancient Theatres and Odea. The ancient Greek and Roman theatres are famous for their excellent acoustics. However, it is not generally well known that different kinds of theatres were built, for different purposes and with different acoustical conditions. The development of the Roman theatre types (theatre, odeon and amphitheatre) particularly in the first Century BC is briefly outlined. One aim of the ERATO project has been to investigate the acoustics of the open air theatre and the odeon, using virtual reconstructions be means of computer models of the spaces, completed in accordance with available archaeological information. Musical instruments and short pieces of music have been reconstructed and recordings have been used for auralisation of some theatre scenarios. Ancient Greek and Roman theatres are often considered acoustically perfect. However, the semicircular shape of the audience area in theatres may cause acoustic problems, and there is also evidence that the ancient architects were aware of this. The Roman architect Vitruvius mentions in his famous books on architecture four different kinds of sound reflections in a theatre, one of them called ‘circumsonant’ which is probably the acoustical phenomenon that we today would name a focused echo. Computer simulations of some examples of ancient Greek and Roman theatres confirm that echo can occur at some places in the audience area. A possible solution to these echo problems could be the introduction of sound absorption in the vertical, concave surfaces in a way similar to that described by Vitruvius for the sounding vessels, i.e. in niches between the seats arranged in a horizontal range halfway up (in the diazoma). Thus it makes sense if the vessels were supposed to act as sound absorbing resonators, although the number of resonators is far from sufficient for having any real effect. The idea and principle of installing resonators in a theatre comes from Aristoxenus (4th century BC), who was a famous Greek philosopher and scholar in music theory. It is concluded that the sounding vessels had no practical importance in the Roman theatres, and Vitruvius was not up-to-date in his writing on theatre design, but relied heavily on older, Greek references.

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1. Introduction

It is impossible to discuss the acoustics of ancient theatres without a reference to the Roman architect Vitruvius and his “Ten Books on Architecture” [1, 2], probably dating from around ca. 30–27 BC. The fifth book is devoted to theatres and their acoustics and while a lot of information has been provided that is important for our understanding of the acoustical design of the ancient masters, the book also contains detailed descriptions about more doubtful “sounding vessels” that have led to many questions and speculations among modern acousticians. It is also important to note that only the older theatres of Greek or Roman type are dealt with, whereas Vitruvius gives no advice concerning the amphitheatre or odeon, which were both very popular newer building types in Roman cities. As a background it is important to have a closer look at the context of Vitruvius’ books, and particularly the remarkable development of theatre types during the first century BC.

The EU project ERATO has dealt with virtual reconstructions and acoustical simulations of selected theatres and odea. Acoustical measurements were also made, particularly interesting in the Aspendos theatre because this is one of the best preserved Roman theatres today. With the characteristic semicircular shape of the Roman theatres it is no big surprise that focusing and echo problems can occur. This was also known by the ancient architects. By means of computer modelling an example of a Roman theatre has been analysed applying an echo parameter. Finally, the sounding vessels described by Vitruvius are discussed. A possible relation with echoes and focusing effects is suggested because the recommended installation of the vessels could make sense, it least in principle, if they should work as resonant absorbers.

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2. Theatres in the Roman Empire

2.1. Types of Roman theatres

2.1.1. Theatre

The ancient Greek theatre had Archaic forerunners from the 5th century BC and developed as an architectural structure during the 4th century BC [3]. The theatres were spread over the Greek cultural area during the following centuries. They were open-air performance spaces related to the religion (Dionysos) and designed for drama performance with emphasis on good speech intelligibility. The theatre and particularly the *skene* building was further developed and improved in the Hellenistic period, and from around the middle of the first Century BC continued by the Romans with further development including an enlarged *skene* building connected to a collonade behind the audience, together forming a semicircular building structure that could be covered with textile like sails as a sunshield (*velum*). Behind the *skene* building a *portico* (nearly square place surrounded with a colonnade) was often an integral part of the Roman theatre complex, as mentioned by Vitruvius [1, Book V.ix.1]. While Greek theatres were built into hillsides, the Roman theatres were generally built on flat ground with access for the audience via *vormitoria* (i.e. entrances for the audience from the outside through narrow passages under the seats of the theatre).

2.1.2. Odeon

The odeon (gr. *ωδεον*, lat. *odeum*) was also originally a Greek building type used for song and music. It was a roofed, columned hall, but the columns disturbed sightlines, as the odeon of Pericles at Athens, built ca. 446–442 BC [4, p. 59]. From the first century BC the Romans developed the odeon into a roofed theatre without columns and with the audience seated in a semicircular arrangement similar to that of the theatre [5]. It is characteristic for the odeon that the building has very thick walls that could carry the roof, and the shape is either rectangular or semicircular, the latter presenting a considerable challenge to structural engineering.

2.1.3. Amphitheatre

The amphitheatre is a space connected to gladiatorial combats as an entertainment, which had its origin in Italy, possibly from the Etruscian or Samnite culture. Traditionally the fights took place in the *Agora* as mentioned by Vitruvius [1, Book V.i.1], but during the first Century BC a specific place for the games was developed, first as a wooden structure, and later as a masonry building [6]. The early versions were called *Spectacula*, a place for watching, and later the name ‘Amphitheatre’ was used. The main characteristics are the oval shaped ‘Arena’ in the middle and the audience seated on all sides around the arena. Like the theatre it was an open-air space with the possibility of a *velum* as a sun shield. It seems that the amphitheatres suddenly appeared in Roman towns and cities, and according to Welch [6] the reason for that was a military crisis in 105 BC when it was decided to use gladiators for training of new soldiers in the efficient use of various weapons. Thus, a connection between gladiatorial combats and military training was established [6, p. 79].

2.2. The development of theatre design during the first century BC

As a background for evaluation of theatre design as described in the fifth book of Vitruvius, it is useful to take a closer look at the development of theatre design in the first century BC.

In Rome it was not allowed to build permanent theatres for political reasons; instead smaller, temporary theatres were built of wood. The first permanent masonry theatre in Rome was built 61–55 BC by Pompey on his private property and he claimed it to be a temple, not a theatre - hence the small Venus temple in the top rear of the audience area. It had room for about 17 000 people. The Marcellus theatre was probably the second permanent theatre in Rome, inaugurated in 13 or 11 BC, but it had already been used for a feast in 17 BC. It seated about 15 000 people. A third theatre in Rome was the Balbus theatre, which might have been earlier than the Marcellus theatre, but little is known about this [6, p. 121].

In Pompeii a lot of building activity started after 80 BC, when it was made a colony for Sulla’s veteran soldiers. Pompeii had already an older Hellenistic theatre from 3rd–2nd century BC, but in addition to this two completely new types of Roman theatres were erected in Pompeii shortly after 80 BC: the odeon for song and music around 75 BC, and the amphitheatre for gladiatorial combats and entertainment with wild animals (lat. ‘*venatio*’) probably around 70 BC [4, p. 174, 177]. The odeon was relatively small and surrounded by thick walls to carry the roof covering both auditorium and stage. Both new buildings were erected under the local reign of Quinctius Valgus and Marcus Porcius, and both building types became very popular in the following centuries as a supplement to the theatre: the odeon in many Roman cities all over the empire and the amphitheatre only in the western part of the empire. The amphitheatre was never adopted by the Greek culture in the east. “*While the Romans built amphitheatres side by side with the theatres, the Greeks built music halls or auditoria even in remote parts of the Greek world during the imperial period.*” [4, p. 222]

In Rome the gladiatorial combats originally took place in the Forum (*Agora*) following ancient traditions in Italy [1, Book V.i.1], but in 30 BC Rome’s first stone amphitheatre was erected by Statilius Taurus as a part of Augustus’ great building program [6, p. 108–127]. Taurus’ amphitheatre may have played an important role as a model for the design on many amphitheatres in the following years. However, the amphitheatre was destroyed in the great fire AD 64. Soon after, the Flavian Amphitheatre (*Colosseum*) was built AD 75–80, a much bigger and structurally advanced masonry building. Only one odeon is known to have been built in Rome, namely by Domitian in AD 86. So, the Taurus stone amphitheatre existed in Rome when Vitruvius wrote his books, and at least 16 other amphitheatres in Italy date to the late republican period [6, p. 191], i.e. they existed at the time of the writings of Vitruvius.

2.3. Theatres in the city plan

The different purpose and use of the various theatres is reflected in the city plan. A very good example is Pompeii, where the theatre and the odeon are in the city centre near the temples and other public buildings, whereas the amphitheatre is located in a remote corner near the city wall. Many Roman towns were founded as colonies where army veterans could settle. This was done already by Sulla (Pompeii, 80 BC) and Julius Caesar (e.g. Corinth, 44 BC) and on a greater scale by Augustus. In all these cases the amphitheatre was a fundamental part of the city plan. *Augusta Praetoria* (Aosta) in Northern Italy was one of Augustus' first veteran colonies founded 24 BC, and both an odeon and an amphitheatre were among the public buildings, being important parts of the city plan, the whole city being surrounded by a high city wall [7]. Another example is *Augusta Emerita* (Mérida) in Spain founded 25 BC as the capital of a new colony. Again the theatre and amphitheatre constituted a fundamental part of the overall urban design. Already after ten years the theatre was inaugurated and a little later the amphitheatre, which was finished in 8 BC.

A typical city plan is also found in Verona with the famous amphitheatre (early 1st century AD) erected in the outskirts of the ancient city, whereas remains of an older theatre and a neighbouring odeon are found further east at the river side, near the original city centre.

3. Vitruvius and his books on architecture

Marcus Vitruvius Pollio was a Roman architect and engineer, known today as the author of "The ten books on architecture" [1, 2]. The exact years of his birth and death are unknown. However, he mentions in the preface of the books that he had served under Julius Caesar during wars. If he means the Gallic wars (58-51 BC), Vitruvius may have been born before or around 80 BC. He mentions that he served to supply and repair *ballistae, scorpiones*, and other artillery [1, Book I.preface.2].

The dedication in the introduction to "Caesar Imperator", i.e. Octavian, suggests that the books were written before 27 BC, because from that year the emperor was given the title "Augustus". This dating coincides with the great building program initiated by Octavian (Augustus) around 30 BC, including the establishing of many colonies and new towns all over the empire. So, presumably there was a need for architectural guidelines in Latin, and Vitruvius was given the task to write such guidelines, since existing guidelines were mostly in Greek language. Thus, Vitruvius draws extensively on older, mainly Greek, writings on architecture and building technology, none of which exists today [1, Book VII.introduction.1]:

> *"It was a wise and useful provision of the ancients to transmit their thoughts to posterity by recording them in treatises, so that they should not be lost, but, being developed in succeeding generations through publication in books, should gradually attain in later times, to the highest refinement of learning. And so the ancients deserve no ordinary, but unending thanks, because they did not pass on in envious silence, but took care that their ideas of every kind should be transmitted to the future in their writings."*

A little later Vitruvius continues in the same manner [1, Book VII.introduction.14]:

> *"... From their commentaries I have gathered what I saw was useful for the present subject, and formed it into one complete treatise, and this principally, because I saw that many books in this field had been published by the Greeks, but very few indeed by our countrymen."*

Concerning his own experience as an architect he mentions, that he superintended the basilica in Fana, Italy [1, Book V.i.6]. This is the only building that we know Vitruvius had actually worked on. It is noted that the Book V on theatre design provides details of the Roman and the Greek theatre. However, the latter were no longer being built, whereas the new Roman amphitheatre and the odeon had already become significant public buildings in the cities, particularly obvious in the new cities founded as a result of Augustus' great building program. But Vitruvius is silent about these buildings, probably because they were not included in the Greek treatises, that he was relying on, and apparently he had no experience of his own concerning theatre design.

4. The ERATO project

The ERATO project was a three year project under the EU 5th Framework "Preserving and using cultural heritage", Project ICA3-CT-2002-10031 running from 1 February 2003 to 31 January 2006 [8]. The acronym refers to the project title: Identification, Evaluation and Revival of the Acoustical Heritage of Ancient Theatres and Odea.

The main objectives of this research were identification, virtual restoration and revival of the acoustical heritage in a few, selected examples of the Roman theatre and the roofed odeon in a 3D virtual environment. The amphitheatres with their clearly different purpose were not included in this project. The virtual restitution integrates the visual and acoustical simulations, and is based on the most recent results of research in archaeology, theatre history, clothing, theatre performance and early music.

The Project group had seven partners:

- The Technical University of Denmark (DTU), Acoustic Technology, Kgs. Lyngby, Denmark,
- Yildiz Technical University, Physics Department, Istanbul, Turkey,
- The Hashemite University, Institute of Tourism and Heritage, Amman, Jordan,
- The University of Ferrara, Department of Engineering, Ferrara, Italy,
- AEDIFICE, Laboratory of Psycho-acoustics, Lyon, France,
- Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland,
- University of Geneva, MIRALAB, Geneva, Switzerland.

Table I. Location and main dimensions of the selected theatres and odea as reconstructed in the computer models. Cavea diameter is up to the last row of seats. The slope is given separately for the lower part (ima cavea) and the upper part (summa cavea).

	Location	Cavea diameter [m]	Orchestra diameter [m]	Ima cavea slope [degree]	Summa cavea slope [degree]
Aspendos theatre	Turkey	84.4	24.0	35	35
Jerash South theatre	Jordan	60.8	18.6	41	41
Syracuse theatre, Roman	Sicily	135.5	30.6	24	20
Aosta odeon	Italy	49.1	12.6	30	30
Aphrodisia odeon	Turkey	42.5	10.0	36	31

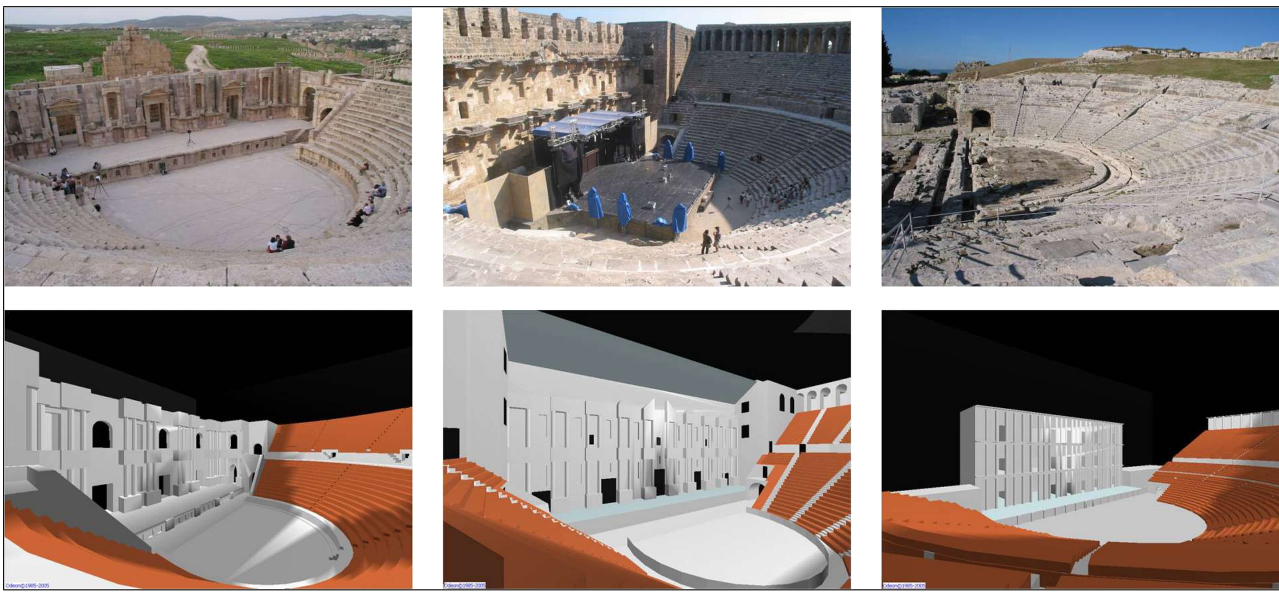

Figure 1. Above: Photos from the three selected theatres, below: View from computer models, reconstructed for the Roman period. Left: Jerash (South theatre), Middle: Aspendos, Right: Syracuse.

The following summary will focus on the acoustical results. The acoustical simulations were made with the room acoustics software ODEON ver. 7.0, developed at the Technical University of Denmark.

4.1. The selected theatres and odea

Five spaces have been selected for virtual reconstruction in the ERATO project: three theatres, see Figure 1, and two odea, see Figure 2. Information about name, location and main dimensions are collected in Table I. In Aspendos the theatre is one of the best preserved examples of a Roman theatre, but in the nearby archaeological site the remains of an odeon are also found. In Jerash there are remains of two theatres, the newly excavated North theatre, which was probably an odeon, and the larger South theatre, which was selected for this project. The theatre in Syracuse has a long history of evolution from Greek to Hellenistic and finally to a Roman style theatre, and it was selected for that reason.

The odeon in Aosta was particularly interesting for this project because this is the only known example where some of the outer walls still exist in full height. The odeon in Aphrodisias was selected because there was very good and detailed information available from the archaeological excavations, and many of the interior details, like statues and marble floor in the orchestra, still exist. However, Aphrodisias also has a well preserved large theatre.

Acoustical measurements were made in the theatres in Aspendos and the South theatre in Jerash. In the theatre of Syracuse and the two odea the state of preservation was not sufficient to make acoustical measurements meaningful.

4.2. Acoustical results from virtual reconstructions

4.2.1. The theatres in Aspendos, Jerash and Syracuse

These three theatres differ in shape and size as well as in the slope of the *Cavea* (the auditorium of the theatre). In Roman times the Syracuse theatre had a colonnade behind the last rows of the *cavea* like the one found at the theatre in Aspendos. The Aspendos theatre had a *Velum* (sunscreen over the audience area) made of wool like a sail and carried by poles or masts, the mounting system of which is still clearly visible. Probably the Jerash South theatre also had a colonnade, but there are no remains left from that and thus no colonnade was included in the reconstruction of this theatre. However, it is very unlikely that the theatre should have been built without the colonnade; it is mentioned by Vitruvius as an important part of the Roman

Table II. Calculated parameters in different configurations (empty and fully occupied) of the theatres. The parameter values are averaged over all source-receiver positions and over mid-frequencies 500–1000 Hz in 1/1-octave bands.

	T_{30} [s]		G [dB]		C_{80} [dB]		STI	
	Empty	Full	Empty	Full	Empty	Full	Empty	Full
Aspendos Roman	1.95	1.59	-2.34	-4.36	1.17	4.08	0.53	0.61
Aspendos present	1.89	1.53	-4.37	-6.09	2.68	6.53	0.60	0.70
Aspendos present (new stage)	1.77	1.43	-4.49	-6.05	4.42	8.27	0.63	0.71
Jerash South Roman	1.54	1.06	-0.72	-3.05	3.46	6.88	0.62	0.70
Jerash South present	1.21	0.86	-1.18	-3.29	5.98	9.85	0.67	0.75
Syracuse Roman	1.81	1.67	-6.69	-8.24	4.07	8.25	0.62	0.70
Syracuse present	1.25	0.97	-10.60	-11.61	12.88	18.12	0.88	0.93

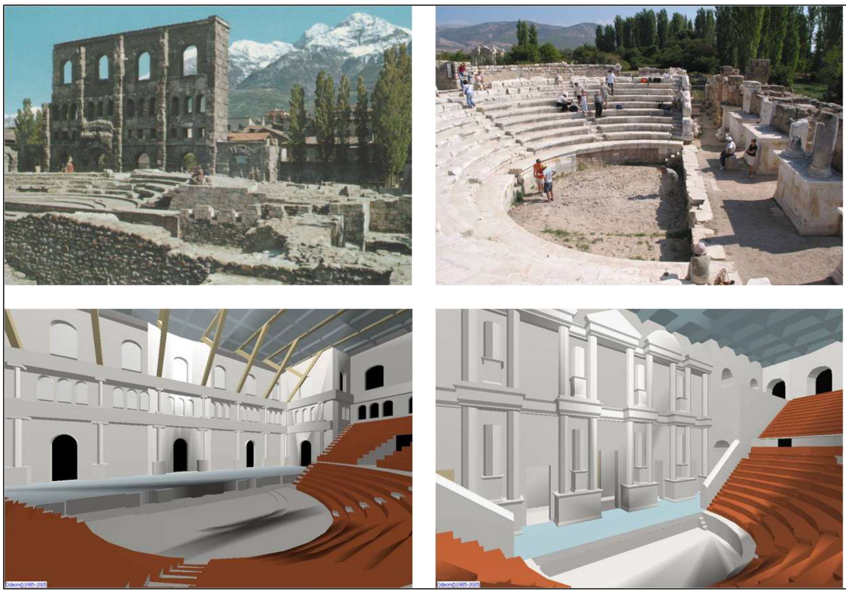

Figure 2. Above: Photos from the two selected odea, below: View from computer models, reconstructed for the Roman period. Left: Aosta, Right: Aphrodisias.

theatre, and it also had a structural function as support for the masts that should carry the *Velum*.

In Table II are shown the acoustical parameters for the three theatres in their different configurations.

The Table II shows that the difference in reverberation time between empty and full is about 0.3–0.4 s generally in all theatres, Jerash South having a slightly bigger difference. The reverberation time when fully occupied is around 1.6 s in the Roman reconstructions with colonnade, but only around 1.0 s in the reconstruction of Jerash South theatre without colonnade.

The overall strength is the highest in Jerash and lowest in Syracuse, partly due to the different slopes and the great difference in *cavea* diameter, see Table I. In general the strength is very low compared to a modern enclosed theatre. The sound field in an open-air theatre is approximately a two-dimensional field, and for that reason the relation between strength and reverberation time is different from that normally found in closed spaces with a three-dimensional sound field.

The clarity is exceptionally high in all the theatres despite the levels of reverberation, and this is due to the lack of roof that make the field more like a free field than a diffuse field. As a consequence of this, the STI values are also remarkably high in theory if we neglect the background noise.

For the Aspendos theatre in present state, the modern stage provides a decrease of reverberation time at mid-frequencies, and in the case of the Roman reconstruction (with added *velum* and stage canopy) there is only minor difference in reverberation.

From Table II it is seen that in Jerash South theatre the reconstruction of mainly the *Frons Scaenae* (the richly decorated front of the *skene* building) results in an increase of the reverberation time of around 0.3 s. It is also seen that the Syracuse theatre in the Roman era had around 0.6 s longer reverberation than in the present stage. This is mainly due to the *Frons Scaenae*, but also the colonnade provided some reverberation.

4.2.2. The odea in Aosta and Aphrodisias

These odea were closed spaces with wooden roof structures; they were used for more intimate music and theatre plays, often only for an exclusive audience. Apart from the roof, they were constructed of hard materials such as stone or marble. They are presumed to have had open windows to let in daylight and provide ventilation. The open windows and audience seated on the cavea would have provided the main acoustical absorption. From Table III one

Table III. Calculated parameters in different configurations (empty and fully occupied) of each odeon. The parameter values are averaged over all source-receiver positions and over mid-frequencies 500–1000 Hz in 1/1-octave bands.

	T_{30} [s]		G [dB]		C_{80} [dB]		STI	
	Empty	Full	Empty	Full	Empty	Full	Empty	Full
Aosta Roman	5.97	3.49	7.14	4.26	-5.28	-2.41	0.36	0.43
Aphrodisias Roman	4.02	1.62	10.45	5.45	-4.21	1.86	0.38	0.55
Aphrodisias present	0.37	0.24	6.42	3.05	15.19	23.21	0.85	0.90

sees that these rooms would have been over-reverberant by present standards.

The Aosta and Aphrodisias odea differ both in their volume and in their shape. The outer walls of the Aosta odeon follow a rectangular shape, whereas in Aphrodisias odeon the shape is semicircular following the seating area. The Aosta odeon had a volume that was almost twice that of Aphrodisias odeon as reconstructed, mainly due to the difference in ceiling height.

By comparing the reverberation times of the two odea as reconstructed to Roman time it is seen, that the Aosta odeon had a longer reverberation time, mainly because of the greater volume.

The present ruins of the Aphrodisias odeon have too few surfaces to provide a reverberant field for satisfactory acoustics as it is seen from the table. The Aosta odeon has not been modelled in its present state, since there is only one wall standing.

In the reconstructed models of the Roman era both odea are over-reverberant when they are empty. The Aphrodisias odeon has a reverberation time T_{30} when full, which is comparable to the optimum for modern concert halls of similar volume. The Aosta odeon seems to be over-reverberant even when full.

The strength G of both odea is seen to have optimum values both when empty and full. The clarity C_{80} of Aosta odeon is too low, mainly because of its high reverberation, whereas Aphrodisias has an adequate clarity. The STI values show that the Aphrodisias odeon is satisfactory for speech when full, whereas the Aosta odeon is just bearable. It has to be mentioned that the background noise level of the audience is not known and probably resulted in lower speech intelligibility.

Overall, the calculation results of the reconstructed model of Aphrodisias odeon have shown an excellent acoustic ambience comparable to modern halls. It must have been a hall that was optimal for music but also acceptable for plays and chorus events. The Aosta odeon would have been less suitable for spoken events but still acceptable for music.

4.2.3. Acoustical scale model investigations

At the University of Ferrara a detailed study was made of the acoustics in different stages of development of the large theatre of Syracuse. From scale model investigations it was found that the different architectural layout of the theatre in the Greek and Roman periods has an influence on the acoustical parameters, and the reverberation time was longer in the Roman theatre than in the previous Hellenistic theatre. This work is documented in two MSc projects and one PhD project [9, 10, 11].

4.3. Reconstruction of musical instruments, music, song, clothes and style of performance

The musical instruments that have been reconstructed are *Kithara* (a plugged string instrument), *Aulos* (a double wind instrument), *Tympanon* (a flat drum) and *Scabellum* (a percussion instrument operated by the foot). The instruments represent Roman times around 1st Century AD, although similar instruments were used also by the Greeks in earlier centuries. Three pieces of music in the antic style have been composed for the instruments and recorded in an anechoic environment.

A database on virtual people has been created, based on historical descriptions of clothes, shoes and hairstyle. The database consists of twelve virtual actors from the Roman period, three actors from the Greek period and a set of virtual musicians. For the virtual audience a crowd rendering and animation machine has been developed. The method allows real-time rendering of thousands of animated virtual humans.

Visual VR reconstructions in computer models have been made for the Aspendos theatre and the Aphrodisias odeon. The models include details like columns and statues, texture to represent the building materials, the coffered ceiling in the odeon and the *velarium* for sun shielding over the open air theatre. Over 150 different textures have been created to represent different surfaces in the buildings. The light conditions can be controlled using a virtual light probe to simulate any position of the sun and condition of the sky.

The visual simulations have been integrated with the acoustical simulations and a number of animated scenarios have been produced, including sounds from the audience.

4.4. Other results from the ERATO project

In relation to restoration works on ancient theatres, new information has been provided concerning the acoustical importance of different parts of the ancient theatres and odea. In the Roman theatre the height of the *skene* building and the decoration with columns and statues are particularly important, but also the colonnade behind the audience is acoustically important. In the odeon the roof and the open windows are acoustically most important; however, it is not very likely that any odeon will be fully restored with a new roof.

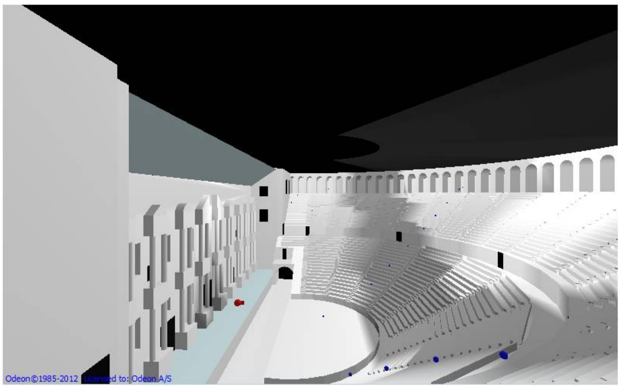

Figure 3. Computer model of the reconstructed Aspendos theatre.

5. Sound reflections in the theatre

5.1. The knowledge of sound reflections in ancient times

Vitruvius describes four different kinds of sound reflections in a theatre [1, Book V.viii.1]; the Greek terms are quoted, and in translation they are named *dissonant, circumsonant, resonant*, and *consonant*. He further explains [1, Book V.viii.2]: "*The circumsonant are those in which the voice spreads all round, and then is forced into the middle, where it dissolves, the case-endings are not heard, and it dies away there in sounds of indistinct meaning. The resonant are those in which it comes into contact with some solid substance and recoils, thus producing an echo, and making the terminations of cases sound double.*"

The reflection called *circumsonant* seems to be the focusing effect from concave surfaces. Although the description is not very clear, it is obvious that the focusing effect increases the risk of echo problems.

5.2. Echo in the theatre

In order to study the possibility of echoes in a typical Roman theatre, the room acoustics software ODEON version 11 was used. The theatre chosen for this study is the reconstruction of the Roman theatre in Aspendos, see Figure 3.

With the source near the centre of the stage at a height of 1.5 m above the stage floor, the early reflections are shown for a receiver position in the orchestra in Figure 4, and for a receiver in a rear position to one side in Figure 5. The focusing of reflections from the concave seating arrangement is clearly seen in Figure 4, but there are also reflections from the concave 'Diazoma' (horizontal passage between several rows of seats) via the canopy above the stage, and late reflections from the colonnade surrounding the theatre. The calculated impulse response in the latter position shows a clear echo with a delay of ca. 125 ms, see Figure 6.

In order to make it possible to locate positions with echo problems, the echo criterion suggested by Dietsch and Kraak [12] has been implemented in ODEON version 11. As an example Figure 7 shows the echo-curve in the same position as the impulse response in Figure 6. The echo parameter has a value above 1.0, which means that

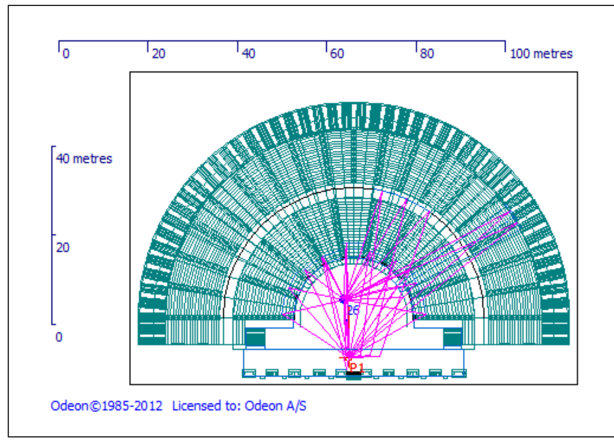

Figure 4. Early reflections from the stage position to a receiver in the orchestra.

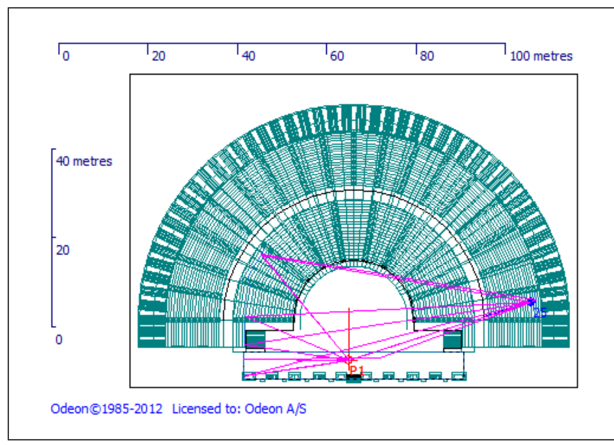

Figure 5. Early reflections from the stage position to a receiver in rear side position.

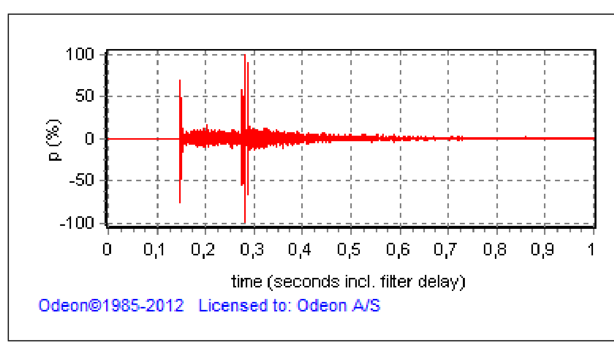

Figure 6. Calculated impulse response in the receiver position from Figure 5.

more than 50% would evaluate this as a clearly audible echo when listening to speech.

6. The 'sounding vessels'

6.1. The purpose

The so-called sounding vessels described by Vitruvius have given rise to much speculation, because it is unclear what acoustical function they could serve in a theatre. They were obviously acoustic resonators, but today

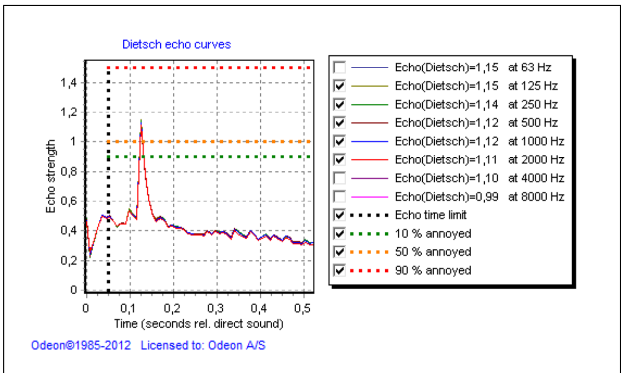

Figure 7. Echo criterion curves for the same position as in Figures 5 and 6. The curves are overlapping for the five octave bands from 125 to 2000 Hz. The peak is at 125 ms.

we know that the effect can either be sound absorption or sound radiation, depending on the internal losses of the resonator. The vessels in the theatre are mentioned several times by Vitruvius, first in book I [1, Book I.i.9]: "*In theatres, likewise, there are the bronze vessels (in Greek ηχεια) which are placed in niches under the seats in accordance with the musical intervals on mathematical principles. These vessels are arranged with a view to musical concords or harmony, and apportioned in the compass of the fourth, the fifth, and the octave, and so on up to the double octave, in such a way that when the voice of an actor falls in unison with any of them its power is increased, and it reaches the ears of the audience with greater clearness and sweetness.*"

The explanation of the purpose [2, Book V.v.3] reads in the translation by Bill Thayer: "*By the adoption of this plan, the voice which issues from the scene, expanding as from a centre, and striking against the cavity of each vase, will sound with increased clearness and harmony, from its unison with one or other of them.*"

In both quotations it is said that the purpose is to increase the clearness. Thus this is the opposite of creating reflections that might increase the reverberance. The description could make some sense if the vessels are meant for sound absorption. The position of the vessels should be under the seats, i.e. in the concave semicircle that can create focusing reflections, and thus the sound absorption by the vessels will attenuate the reflections that might cause an echo problem.

Today it is well known that sound absorption is possible with Helmholtz resonators. However, they are only efficient in narrow frequency bands. So it also makes sense to apply different sizes with resonance frequencies distributed over two octaves, as described in detail by Vitruvius. This may correspond to the frequency range 220–880 Hz as suggested by Barba Sevillano *et al.* [13]; this paper contains a thorough analysis of the frequencies of the vessels in relation to the ancient Greek musical system developed by Aristoxenus.

Another remark from Vitruvius, that is interesting in this connection, is in [1, Book V.v.7], where he says that there is no need for the sounding vessels in the wooden theatres that were built every year in Rome, because the boarding itself is resonant – "*But when theatres are build of solid materials like masonry, stone or marble, which cannot be resonant, then the principle of the 'echea' must be applied.*" As we know today, the low frequency absorption can be obtained with panel absorbers, which would be more efficient than the rather small number of Helmholtz resonators recommended by Vitruvius.

It is interesting to note that Vitruvius uses the word *echea* (ηχεια) which in modern Greek means a loudspeaker system. The sounding vessels were discussed in some detail by Izenour [14, p. 34] and with reference to Vitruvius [1, Book V.iii.8] he suggests an explanation: "*The ancients, using commonsense reasoning, considered it perfectly obvious that if resonators or sounding boards of bronze or horn were used to strengthen the sound produced by a string or wind instrument, the same would hold true for the arrangement of a theater in accordance with the science of harmony, because in this way (Vitruvius says) the Greeks increased (amplified) the power of the speaking voice.*" At the end of this discussion Izenour concludes [14, p. 39]: "*What charming nonsense!*"

6.2. The origin of the sounding vessels – Aristoxenus

Concerning the principle behind the sounding vessels and the musical scales used for the tuning, Vitruvius refers to the ancient Greek music theoretician and philosopher Aristoxenus [1, Book V.v.6]. He lived in Athens around 350 BC, was a pupil of Aristoteles and wrote a large number of treatises on topics within music, ethics and philosophy. His theory on musical scales was in opposition to the one by Pythagoras based on mathematical principles. Aristoxenus claimed that the superior evaluation of musical intervals should be made by the human ear. He said that we evaluate the size of the intervals by the ear, and the properties by the brain. In fact he suggested the equally tempered scale more than two thousand years before this scale became generally accepted in the 18th century.

6.3. Where did they exist?

The evidence of the existence of sounding vessels in theatres is very sparse. Obviously Vitruvius has never seen them himself, but he refers to [1, Book V.v.8] "*... the districts of Italy and in a good many Greek states. We have also the evidence of Lucius Mummius, who, after destroying the theatre in Corinth, brought its bronze vessels to Rome.*" It is a fact that Lucius Mummius was a Roman general who conquered Corinth in 146 BC, demolished the city and brought lots of treasures to Rome. The theatre was a Hellenistic theatre from the 3rd century BC [3]. The time and location of this theatre fit quite well with those of Aristoxenus, see above.

Izenour has described the existence of nine equally spaced cavities located behind the diazoma in the ruins of a Roman theatre in Beth Shean, Israel [14, p. 39–40]. Although the number should have been 13 according to Vitruvius, and not only nine, Izenour has shown in sketches how the vessels might have been installed in the cavities.

In 1958 some clay vessels were found when a theatre was excavated in Nora, Sardinia. The site was visited by Dr. Brüel, who made a photo of the vessels together with other observations [15, p. 18]. However, he concludes that from the findings there is nothing making it likely, that the vessels have improved the acoustics of the theatre in any way.

So, the sounding vessels did actually exist in some theatres, but only in very few rare cases. In the vast majority of Greek and Roman theatres the sounding vessels were not used.

6.4. The sounding vessels, a summary

The idea of installing resonators in a theatre dates to Aristoxenos, i.e. to the early days of the Greek theatre. Although it theoretically could make some sense as a measure against the focusing of sound from the concave shape of the stone seats in a theatre, the very small amount of absorption that can be obtained in practice makes it clear, that the sounding vessels had no audible effect when installed in a theatre. It is clear that Vitruvius had no experience with theatre design, but in his work dealing with translation of old Greek treatises on building design he probably found the idea of the sounding vessels so fascinating, that he decided to promote it. However, as concluded in section 3, Vitruvius was not up-to-date in his book on theatre design, and therefore it is most likely that the architects responsible for the building of Roman theatres, odea and amphitheatres have simply ignored Vitruvius' advice concerning the sounding vessels.

7. Conclusion

The results from the ERATO project of the acoustical simulations in the reconstructed theatres and odea confirm the assumption, that they were dedicated for different purposes. The theatres with very high clarity of sound were excellent for speech, whereas the odea with a higher sound strength and more reverberant sound were excellent for song and music from weaker instruments like the lyre or kithara. More information can be found in the final project report [8] and in the proceedings of the ERATO project symposium [16]. Detailed studies on the acoustics of ancient theatres are described in a PhD thesis by Farnetani [9].

Echo problems can occur in certain places in the ancient theatres, particularly in the orchestra area due to the focusing effect of the concave shaped steps of seats. In this respect the *diazoma* is particularly important because of the higher wall, and this is precisely where the sounding vessels described by Vitruvius should be installed. It appears that the idea and the guidelines for the sounding vessels go back to Aristoxinus in the 4th century BC, in those days a famous scholar in music theory. From the description given by Vitruvius, and the collection of information from excavated theatres where the vessels might have been installed, it is concluded that the sounding vessels could not possibly have made any improvement to the acoustics in practice. It seems that Vitruvius' efforts to promote these ancient ideas for Roman theatres have been more or less ignored by those, who actually were responsible for designing and building the theatres.

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