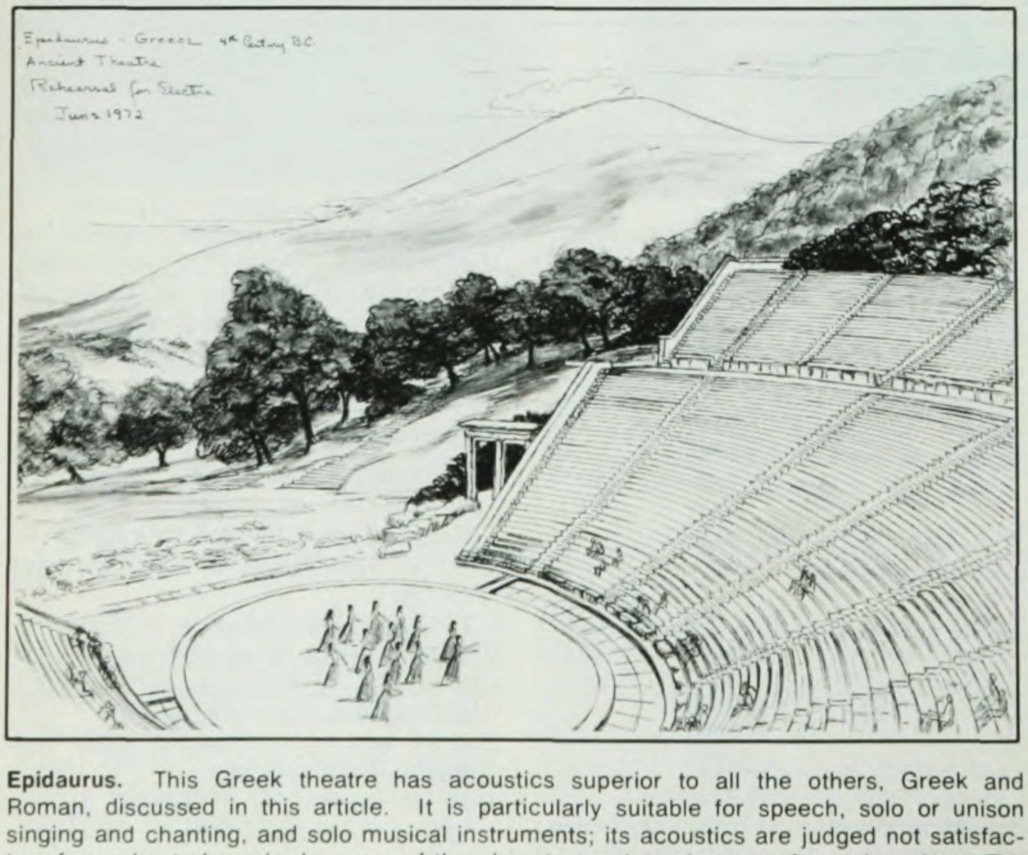
Acoustics of Greek theatres

Robert S. Shankland

The best of the classical Greek theatres have remarkable acoustics for speech intelligibility, solo or unison singing, chanting, and for solo musical instruments. The essential property of the theatre structure to achieve this condition appears to be the architectural features that produce a profusion of "early reflected sound," that is, sound reaching the listeners within 50 milliseconds of the direct sound, scattered by both seats and people. To a lesser degree, sound reflected from the orchestra and stage house appears to be important when these (as in the original Greek structures but not in the later Roman theatres) provide a spectrum of early reflected sounds with time delays of 20 millisec or less following the direct sound. The almost complete absence of reverberation and a wide spread of time delays (50 milliseconds or more) in the reflected and scattered sound make Greek theatres unattractive for orchestral music. But for their principal purpose of play production they were excellent, and when we consider that they employed no sound amplification but only strenuous effort by the performers, they are truly remarkable acoustical achievements.

In this article I shall describe studies of the acoustics of ancient theatres made in Italy in 1964 and 1966, in Sicily in 1968, and in mainland Greece in 1972. The earlier work in Sicily and Italy had led to certain conclusions[1] on the acoustics of classical theatres, and it was felt desirable that these results be supplemented by studies of theatres in mainland Greece. Buildings visited and studied included the Roman theatres at Ostia Antica and Fiesole in Italy, Greek theatres at Taromina, Segesta and Syracuse in Sicily, and theatres in mainland Greece at Epidaurus, Delphi, the theatre of Dionysos at Athens and the Odeion of Herodes Atticus, also at Athens.



Epidaurus. This Greek theatre has acoustics superior to all the others, Greek and Roman, discussed in this article. It is particularly suitable for speech, solo or unison singing and chanting, and solo musical instruments; its acoustics are judged not satisfactory for orchestral music, because of the almost complete absence of reverberation. The theatre, 387 feet in diameter, can accomodate an audience of 14 000. Figure 1

Epidaurus

The observations confirm the generally accepted view that the theatre at Epidaurus is by far the most suitable for detailed acoustical analysis because of its excellent state of preservation; nearly all the seats are in their original places, with only a small amount of expert restoration. This theatre was designed in the middle of the fourth century BC, in all probability by a highly skilled architect (although his identity is in question[2]), and its reputation for excellent acoustics is well deserved. Figure 1 shows the essential features of the Epidaurus theatre that are important for its acoustics. It can accommodate 14 000 people in 55 rows of seats, 34 rows below the horizontal cross aisle, or diazoma, and 21 rows above. The lower section is divided by radiating aisles of steps into 21 wedge sections of seats (cunei), and the upper part is further divided by additional intermediate aisles. The theatre is 387 feet in diameter, and the orchestra is a complete circle, 67 feet in diameter. The classical Greek theatres had packed earth orchestras; only when they were modified later in Hellenistic times were marble or other stone surfaces installed, similar to the orchestras of Roman theatres.

The acoustics of the Epidaurus theatre are superior to all others that I have

Apparently it is the detailed geometry of the seating area that gives the best classical Greek theatres their excellent acoustical qualities for speech and solo performances.

studied. Although not "perfect," they are certainly remarkable. Numerous speech-articulation tests were made at Epidaurus, as were observations of sound propagation, speaking, singing, and a rehearsal of Sophocles's "Electra." The sound-propagation observations confirm the uniform distribution of sound intensity and its regular attenuation with distance from a source in the orchestra reported[3] by B. Papathanasopoulos.

The effects of various sounds and noises generated in the orchestra, on a temporary stage, and at locations behind and at the sides of the stage, including carpenters hammering and electronic effects for "Electra," were also observed. There is no single factor giving the theatre at Epidaurus its excellent acoustics as compared to the others studied; rather it is the cumulative effect of many refinements in design, construction and the present excellent state of preservation that all contribute to its acoustical superiority, especially for speech intelligibility. These studies suggest that the major factor for the acoustics at Epidaurus is the perfection of the geometrical arrangement of seats relative to the performance areas in the orchestra and stage, which results in many early reflected sounds being received by all listeners in the cavea soon after the direct sound is heard.

Early reflected sounds

As first shown by Joseph Henry (in experiments at the Old Smithsonian Building in Washington) early reflected sounds, reaching a listener within 50 milliseconds after the direct sound, combine without echo to produce in the listener's consciousness a single acoustical image of greater intensity and enhanced quality than that of the direct sound alone.

Early reflected sounds in the empty theatre—the condition usually observed by visitors—are produced primarily by scattering of sound from the stone seats. When the theatre is occupied some sound is scattered from exposed stone, but most of the scatter is from the audience, and especially by bare heads; although unoccupied seats scatter more sound than an audience, the latter is nevertheless highly effective. Furthermore, scatter by an audience produces much less backscattered sound toward the orchestra and front seats. This is because sound (especially the higher frequencies essential for speech intelligibility) is diffracted by the heads of the audience mostly through relatively small angles,[4] whereas that scattered by the seats includes much sound energy reflected through large angles. Large-angle scattering results in poorer listening conditions in seats near the front and at the extreme sides of an empty theatre as compared to an occupied one.

So we see that the acoustical excellence of the best Greek theatres is due primarily to the spectrum of early reflected sounds reaching a listener by scattering from the audience and empty seats. Because there are no sound-reflecting side walls or ceilings

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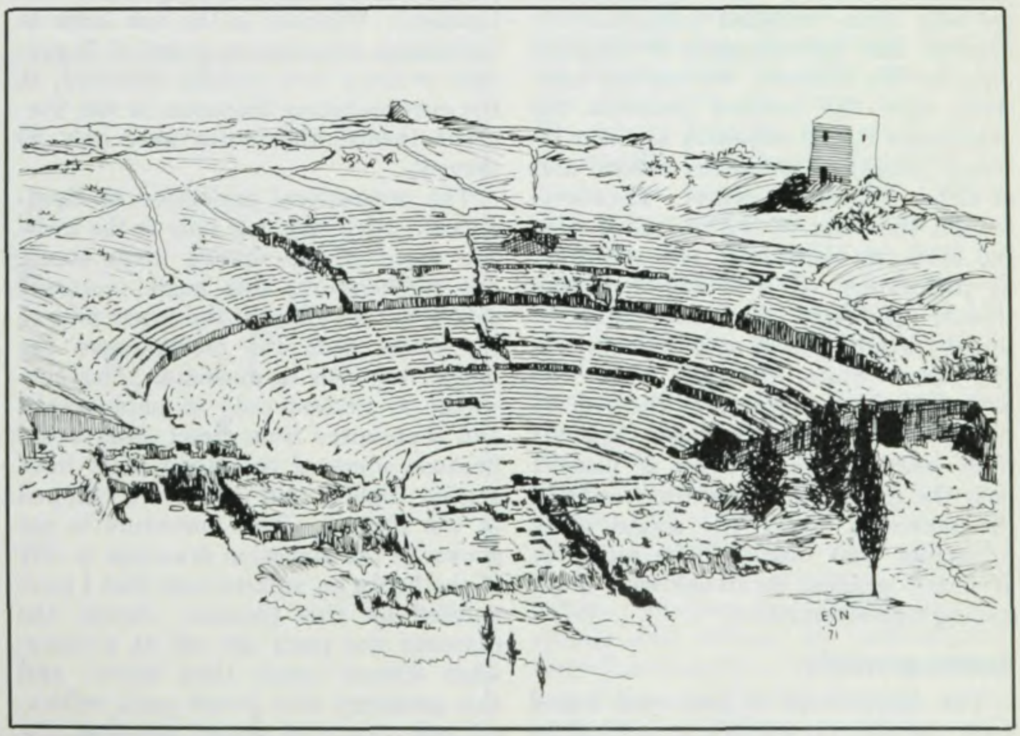


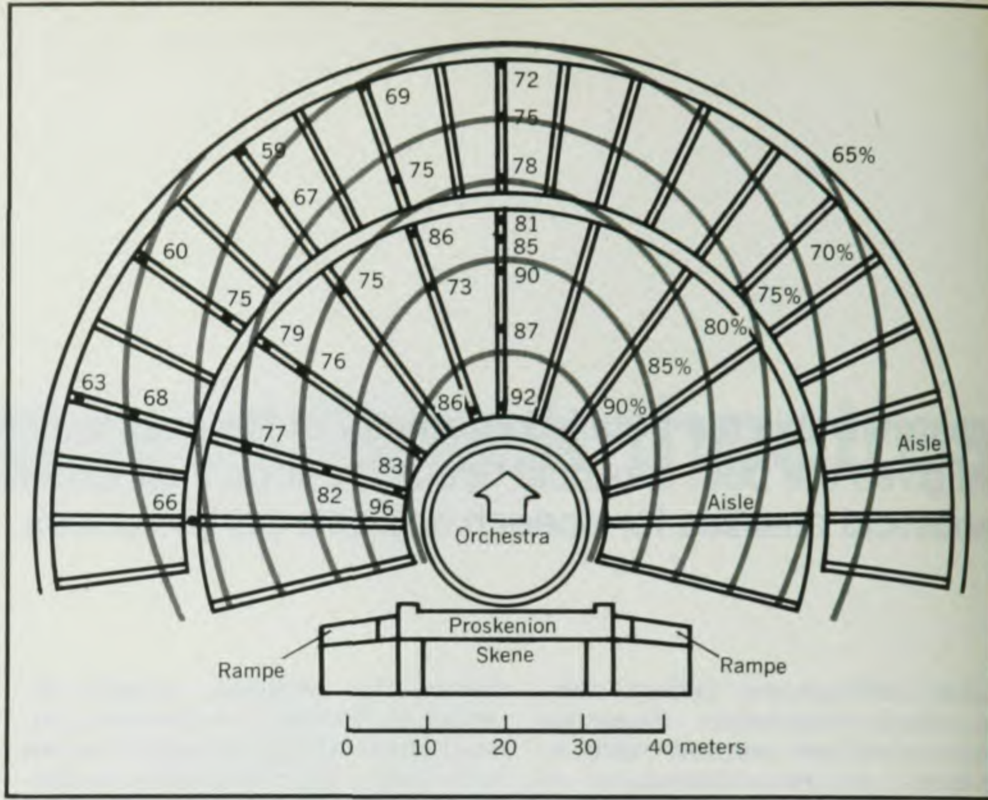
Syracuse. The natural topography at this Sicilian site was exploited in the construction of the Greek theatre; note that the seats are cut into the native rock. But the result is that the slope of the rear seating areas is less than it is for the forward seating, contrary to the requirement for good acoustics, and this theatre is judged not as successful as the one at Epidaurus. The two drawings on these pages are by Mrs. Shankland. Figure 2 in these structures, no early reflected sound of the kind prominent in good concert halls can reach the listener. Exceptions to this are where the stage has an extensive and detailed architectural structure, as at Taromina in Sicily and Herodes Atticus in Athens, but in general the stage house (skene) is either absent or, if installed temporarily for a summer program, is not a primary factor for directing sound to the audience.

The spectrum of early reflected and scattered sound in a Greek theatre is made up of many impulses of sound energy arriving within 50 milliseconds after the direct sound. As a result, the sound spectrum perceived by a typical listener approximates a continuous distribution decreasing steadily in intensity with increasing delay time, because for the longer delay times sound is scattered through larger angles with less intensity. Consequently for seats at greater distances from the stage the angles at which scattered sound reaches the listener become progressively smaller. Thus, toward the rear of the theatre, even though the total intensity is reduced, the clarity or "refinement" of the sound improves, especially for speech. These factors, and the almost total absence of reverberation, account for the fact that hearing conditions at the rear of a large classical theatre are excellent.

These conclusions are supported by discussions with Alexis Dimitropoulos, professor at the Athens Theatre School, with actors and actresses during a rehearsal at Epidaurus of Sophocles's "Electra," and also with others who have attended numerous rehearsals and performances of classical plays in this theatre. We learned from them that the favored positions for performers in the orchestra are near its center (focus) or somewhat behind and at either side of the center. Locations toward the front of the orchestra near the seats are considered less desirable by performers. It is evident from the theatre geometry that the paths of sound travelling from actor to audience are much more effective when the actor is near the center or the rear of the orchestra or on the stage (logeion) than when the performer is located near the front or at the extreme side of the orchestra where the sound must propagate over much of the audience at nearly grazing incidence with a resulting high attenuation.

Seating geometry

The importance of scattered sound from the cavea is strongly supported by speech articulation tests made in the theatre at Syracuse in Sicily, where the natural ground topography (see figure 2) makes the slope of the rear seating areas less than it is for those toward



Articulation scores determined at various points in the Epidaurus theatre, with averaged contours shown in gray. The scores are arrived at by reading aloud from word lists at the center of the orchestra and noting the number of words correctly heard at different points in the cavea. Note the relatively high scores in the rear seats. Figure 3

the front. Articulation scores in the upper seats of the Syracuse theatre fell off much more rapidly with distance from the speaker in the orchestra than can be attributed simply to the increased distance from the orchestra. (An articulation score represents the number of words, read from a specially prepared word list, correctly heard by a listener.) Whereas in the rear seats at Epidaurus articulation scores of 70 percent or more were usually obtained, at the corresponding locations in the Syracuse theatre the scores were only 50 percent.

The geometrical perfection at Epidaurus is such that not only is the average angle of the seating areas steep, but furthermore, this angle increases slowly but steadily in the lower part of the cavea from the orchestra to the main cross aisle or diazoma. This curvature is evident only in photographs and is obscured from direct observation because some of the stone seats have settled slightly and others are chipped at the corners. This curvature is not shown in the elevation drawings in any of the books on architecture that I have studied on this theatre. Above the diazoma the seats are set at a somewhat steeper angle than below, and this geometry also favors early reflected and scattered sound reaching the audience, especially near the top of the theatre where tourists are usually stationed for demonstrations of the acoustics. All the observations support the proposition that early reflected sounds made possible by cavea geometry are highly important—indeed, decisive—for the acoustical excellence of Greek theatres. Some early delayed sounds are also reflected from the orchestra floor and the stage house, but the major contributions are by sound scattered from seats or audience in the cavea. This conclusion is supported by the fact emphasized by Dimitropoulos that at Epidaurus the acoustics are nearly unimpaired when the temporary stage house is absent.

Inspection of the seating geometry at Epidaurus also reveals that the rows of seats in the upper section immediately above the diazoma can receive but little early reflected sound from the lower seating areas. This correlates with the results shown in figures 3 and 4, which demonstrate that the listening conditions beyond the diazoma are not as good as would be expected simply on the basis of distance from the orchestra and are markedly poorer than for seats just below the diazoma. It is to help overcome this defect that the seats above the diazoma are set at a steeper angle than those below. This design improves the listening conditions in the extreme upper rows of seats, but to a lesser degree for seats immediately above the diazoma.

Note in this connection that this geometry, which produces less favorable listening conditions immediately above the diazoma, does not interfere with the spectator's view of the orchestra. This supports the belief that visual and not acoustical criteria dominated the architectural design. No written evidence has been found to suggest deliberate architectural design objectives relating seating geometry and acoustics, and it appears probable that the architect was concerned primarily with visual requirements. The best seeing would be obtained by gradually increasing the slope of the cavea from front to rear, and this is also excellent for the acoustics.

Echo tone

At Epidaurus the central sections of seats have their focus at the center of the orchestra, but the projected extensions of the radiating aisles of the two wedges of seats at either side below the diazoma (and their continuation above) have their focal points located at either side, behind and beyond the center of the orchestra. This seating layout may have been designed to improve the visibility of the orchestra from the side sections of seats. But the acoustical effect of these three foci is important in that there is a much less pronounced echo "tone" observed near the center of the orchestra from the empty theatre at Epidaurus than in well preserved Roman theatres, such as those at Ostia Antica and at Fiesole, where all rows of seats are located on perfect circles and so have a common center of curvature at the middle of the orchestra.

The echo "tone" from an impulsive sound is produced by the constructive interference of sound waves scattered back to the orchestra by successive curved rows of seats. For perfect seat geometry, the "tone" is harsh, because of the constructive interference of strong high harmonics. In less perfect theatres the fundamental tone predominates, but when an audience is present, or where the seating geometry has greatly deteriorated, the "tone" is weak or absent. However, even under these circumstances, much incoherent sound is scattered back to the orchestra and stage, an essential condition if the performers are to hear themselves properly.

During rehearsal the echo "tone" from the empty seats can be annoying to the actors, and it is possible that the Epidaurus architect may have deliberately defocused the side sections of seats from those at the center to reduce the echo perceived in the orchestra and thus improve the acoustical conditions during rehearsals. The usual explanation given—that the objective was to improve the visibility for spectators in the side seats—is hardly valid because the change in seat orientation is so small. However, these small changes in orientation are all that are needed to make a great reduction in the acoustical focusing.

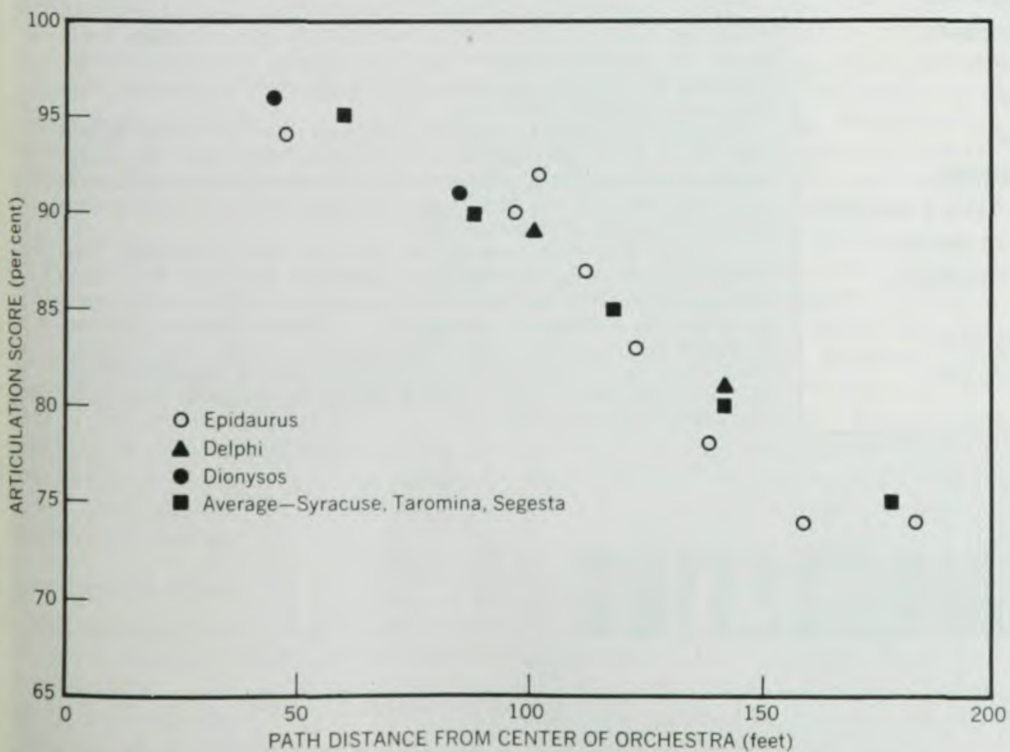
Other theatres

Observations in several other theatres in mainland Greece and Sicily confirm these general conclusions and provide important additional data. The theatres studied in greatest detail were those of Dionysos at Athens, the Odeion of Herodes Atticus in Athens, and the theatres at Delphi, Segesta, Syracuse and Taromina. The theatre at Delphi is rather well preserved, and the tests revealed that it has excellent acoustics. Here I was able to make a number of acoustical observations in addition to speech-articulation scores.

One result, shown in figure 4, is that speech intelligibility is high even at the rear center of the cavea, although the side seats at Delphi do not extend to form complete semicircular curves as at Epidaurus. This indicates that the most useful early reflected sounds reaching a listener at the rear center of a theatre are those scattered through relatively small angles by the central wedges of seats. These delayed sounds have the greatest intensity and shortest time delays. Sound scattered by seats at the extreme sides (if present) would be delayed for much longer times and would therefore impair speech intelligibility; however, because sound scattered through large angles is greatly reduced in intensity, the effect of scattered sound from seats at the extreme sides of a theatre is often not noticed. At Epidaurus and other large theatres such as Syracuse where the side seats of the cavea form arcs greater than complete semicircles, hearing in the front sections of the theatre and at the extreme sides is often harmed by these long-delayed sounds, especially when the side seats are unoccupied. This condition cannot occur at Delphi.

A performance of Mozart's Coronation Mass in the Odeion of Herodes Atticus provided an opportunity for subjective judgment of its acoustics, complementing various acoustical and articulation tests made in the empty theatre. Hearing conditions were observed during the concert at two locations in the auditorium; one location was towards the side near the front of the theatre, and the other was on the axis just below the main cross aisle. The second location was much better acoustically. Although excellent for music, the acoustics of this Odeion, both empty and when occupied by an audience, are not nearly so good for speech as Epidaurus, and I learned from friends in Athens that this Odeion is generally considered inferior to Epidaurus for plays. This is because Herodes Atticus has a high and deep stage house, of heavy stone construction, that produces strong reflections with time delays for the audience longer than the optimum 20 milliseconds. These long-delayed sounds are not loud enough to produce noticeable echoes, but they nevertheless blur the speech and reduce its intelligibility. Speech-articulation studies by François Canac in Roman theatres at Orange and at Vaison in France show these same effects.[5]

In the classical Greek theatre the sound-reflecting walls of the stage house were near the actors (say, within ten feet), so that the time delays of the



Comparison of several theatres in Greece and Sicily. In each case articulation scores were determined at locations along the central radial aisle. In the Syracuse theatre the articulation score dropped to 50% at a distance of 210 feet. Figure 4

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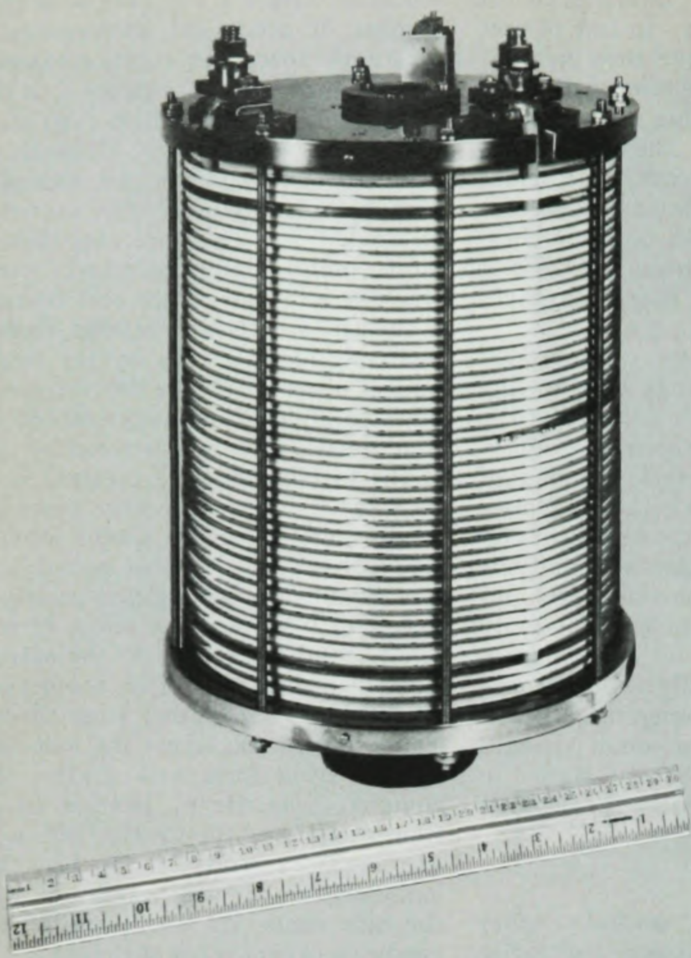

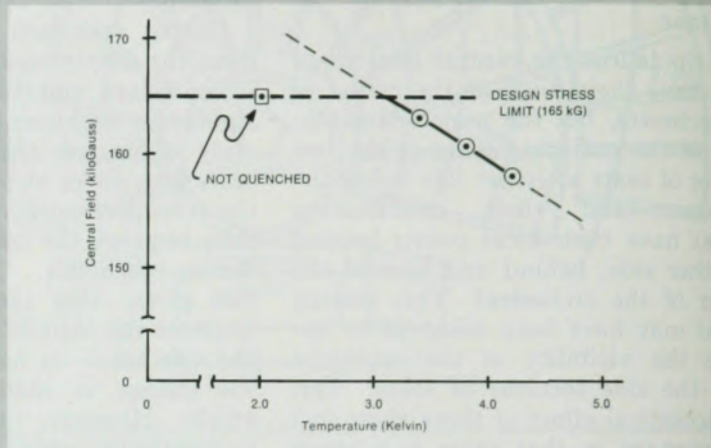

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Quench Field at 4.2K	158 kiloGauss
Quench Field at 3.0K	165 kiloGauss
Clear Bore Diameter	25.7 mm
Outer Diameter	231 mm
Length	262 mm
Operating Current at 150 kG	126 Amperes
Field Homogeneity at 150 kG	3×10^{-4} in a 5 mm DSV
Time to 150 kG (Virgin Run)	Under 30 minutes
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Weight	66 kilograms
Average Current Density in Winding Space at 165 kG	15,500 A/cm^2

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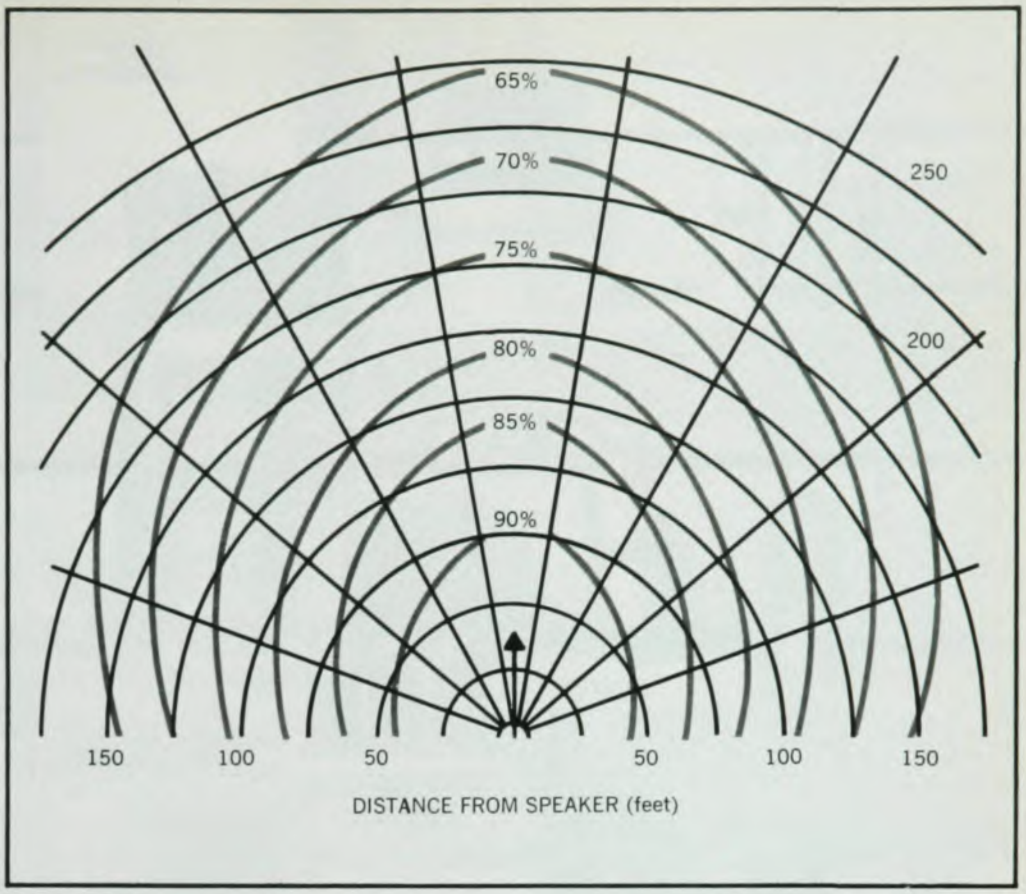
reflected sounds were all short and well within 20 milliseconds. However, Herodes Atticus is superior to Epidaurus for orchestral concerts, primarily because of the large sound-reflecting and sound-diffusing structure of stonework behind and at the sides of the stage. This gives excellent blending of sounds and increased intensity for orchestral music, and long time delays that would be excessive for good speech intelligibility or soloists but are acceptable and indeed desirable for symphony. The longer time delays also give a character to the orchestral music in Herodes Atticus not dissimilar to that produced by reverberation in an enclosed concert hall. In this connection, the observations at Epidaurus lead to the belief that the excellent acoustics of the classical Greek theatre for plays did not depend greatly on the sound-reflecting properties of the walls of the stage house. During the Epidaurus tests there was no permanent stage structure, only temporary wooden platforms for rehearsals, yet the speech intelligibility even in the rear seats was excellent. Thus, the acoustics for speech appear to be unimpaired by the absence of a stage house and to depend primarily on the sound reflected from the orchestra surface and the many early reflected sounds that reach the listener by scattering in the cavea.



Averaged contours for speech articulation determined in several Greek theatres, weighted somewhat for the results obtained at the Epidaurus theatre. Figure 5

The enhanced level of loudness and speech intelligibility caused by the profusion of short-time delayed sound in Greek theatres is also beneficial for singing, and for solo instruments such as the flute and the ancient lyre. However, for orchestral music these theatres are not exceptional. Balance between instruments is not achieved, and the blend of tone essential for ensemble effects with groups of instruments is absent. Also the complete absence of reverberation is highly detrimental for orchestral music. Musicians in Greece told me that even the Epidaurus theatre is not satisfactory for orchestral music.

Figure 5 gives the averaged contours of speech articulation as determined in several theatres studied, weighted somewhat for the results obtained at Epidaurus. The superiority of Epidaurus for listening to speech is most striking in the distant seats where the excellent geometry (as contrasted to that at Syracuse, for example) produces its full effect.

Background noise

Background noise and wind are extremely important factors for speech intelligibility in outdoor theatres. Both at Epidaurus and at Delphi the measurements reported here proceeded during unusually favorable conditions, except on a few occasions. But observations at these exceptional times gave useful data for determining the effects of noise and wind. In the two theatres in Athens (Dionysos and Herodes Atticus) street noise was often a problem, although the measurements were usually made at times to minimize this disturbance. Comparison of the Athens results with those obtained under very quiet conditions at Delphi and Epidaurus shows that the effect of noise in an outdoor theatre on listening conditions for speech is quite different from the effect of indoor noise, which gives rise to masking reverberation. All types of indoor noise are harmful for speech intelligibility, and outdoors a continuous noise such as heavy street traffic causes masking effects like those experienced indoors. But, intermittent noises such as talking, carpentry, and so on, interfere much less with speech intelligibility outdoors than they do indoors where they are prolonged by reverberation. For example, a listener on the diazoma at Epidaurus could clearly hear low-intensity speech from the orchestra, in spite of simultaneous conversations by tourist groups in other parts of the theatre. In contrast, steady street traffic near the theatre of Dionysos in Athens greatly interfered with hearing conditions. Wind (even when moderate) blowing past the listener produces a dramatic reduction in speech intelligibility. For example, tests made in the Roman theatre at Ostia Antiqua near Rome gave articulation scores that changed from 80% to 40% when a moderate breeze began to blow. However, Greek theatre sites were usually chosen at locations on hillsides where the wind was not a problem—a criterion seldom observed by the Romans.

We conclude, then, that the classical Greek theatres—especially the fine structure at Epidaurus—have excellent acoustics for their purpose, superior both in architecture and siting to the later Roman theatres of the same type. It is probable that their designers worked largely with visual considerations—provision of good sightlines for the entire audience—rather than acoustical matters in mind, in which case we are fortunate that the two go together to provide high-quality outdoor theatres. We are fortunate also that these structures still exist, more than two thousand years later, for our study and our pleasure.

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