EARLY LATERAL REFLECTIONS IN SOME NEW CONCERT HALLS *)

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INTRODUCTION

When Leo Beranek [1] compared many concert halls he found that in those with the best reputation the direct sound is followed very soon by "early reflections". Marshall [2] emphasised that these early reflections should also be lateral. Barron [3] concluded from careful subjective experiments that the special hearing event of these "early lateral reflections" is not reduced if some reflections from the ceiling arrive even earlier. He, and more recently, Blauert and Lindemann [4] studied the conditions for the corresponding "sound events" very extensively. I have to thank both for very informative correspondence, but I shall not discuss these problems now.

Here, I restrict my "hearing events" only to the <u>awareness</u> of lateral reflections, calling special attention to the remarkable non-linearity of this phenomenon. I have observed in the Berlin Philharmonic Hall that in <u>piano</u> (very soft passages) the source seems to be concentrated on the stage but in <u>fortissimo</u> the walls themselves seem to be playing [5]. I explained this effect, on the basis of investigations by Wettschureck [6], in terms of the non-linearity of the log(loudness)-L function. Thus, a loudness ratio of 4:1 at a low playing level can fall to 2:1 at a higher level. The fact that nearly all instruments produce more overtones at higher levels may also play a role.

This just emphasises the well-known experience that the awareness of lateral reflections and their directions of arrival increases with increasing frequency. It corresponds also to my experience that even small sound reflecting panels (which reflect geometrically only at high frequencies) are suitable for providing perceptible lateral sound reflections. Without this conviction, I could neither recommend light-ray models nor the use of reflecting steps of 2 m for the effective creation of lateral reflections. I even consider it an <u>advantage</u> that such panels do not direct the low-frequency first-reflected sound towards the sound-absorptive audience, and therefore do not deplete the low-frequency energy in the reverberation, where it plays a more important role.

EL AUDITORIO NATIONAL IN MADRID

The first example is a pure concert hall for 2200 listeners. It solves the problem of lateral reflections by adapting from the classical halls, a geometry of parallel sidewalls with moderate hall width. It avoids seating listeners more than 39 m from the stage by placing a small part of the audience behind the stage. The architect, Garcia de Paredes (Madrid), had already used this principle with great success in a smaller concert hall for 1200 in Granada: the De Falla Hall. There, about one-third of the audience was seated behind the stage.

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In both the Granada and Madrid projects I worked with my Berlin colleague, Thomas Fütterer, as acoustic consultants to Architect Paredes. We knew already, from the Berlin Philharmonic Hall, that it is not the seats behind the orchestra that create the problems. For most listeners here, small acoustic imperfections in orchestral balance and timbre are more than compensated by being able to watch the conductor's face. The only true handicap is presented by vocalists, both because of the directional characteristics of their voices and because of the visual deprivaton.

The most important consequence of omitting large lateral audience areas was being able to retain some lateral walls rather close by. Figure 1 shows a plan view of the highest audience floor in the Madrid Hall and Figure 2 shows a cross-section. Listeners are placed behind the chorus on both sides of the organ and, in order to achieve the desired seating capacity, an overhanging Balcony five rows deep is formed on each side of the stage.

The sidewall below this Balcony encloses the Stalls with only a narrow side aisle and this wall, together with the reflection from the balcony soffit, provides adequate lateral reflections. The same situation arises above the Balcony, where the last two rows are covered by a convex-shaped reflecting panel. This shape broadens the usual "cornice" reflections across the Stalls. A similar panel is repeated above the next level which contains the King's Box on one side and smaller boxes on the other side. Furthermore, all the balustrades are so inclined that at the sides of the stage they reflect sound back to the musicians, and at the sides of the Stalls they reflect sound to the audience.

In earlier times the disposition of audience seating in the acoustical design was only a question of access, aisles and staircases, etc. Nowadays, in addition, we must take account of the seating arrangement in order to provide suitable lateral sound reflections.

We tried to optimize the sidewalls, steps and balustrades with the help of a light-ray model at 1:50 scale; using a laser directed from outside the model onto a mirror on stage and small mirrors glued to each surface of interest. This may appear rather primitive to the acoustical scientist but for the consultant, it provides a lucid demonstration to the architect who could even make use of it himself.

THE APOLLO HALL IN NICE [7]

(Architects: Buzzi, Baptiste & Bernasconi, Nice; room acoustics consultants: Lamoral, Cremer and Fütterer).

The opportunity to place as much as one-fifth of the audience behind the stage vanishes immediately when the hall must accommodate staged productions, for example opera, which requires a large stage house and many other ancillary backstage facilities. I was presented with such a problem in the Apollo Hall in Nice, an auditorium for 2500 which is part of the "Acropolis" cultural centre and is also used for large congresses.

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Although the disposition of audience seating is somewhat peripheral to our present topic, it is of interest. The audience is distributed over one Balcony and a large Stalls section (see the longitudinal section in Figure 3 and the plan in Figure 4). The audience is divided by "vineyard steps", as in the Berlin Philharmonic Hall, but this time those steps are oriented towards the stage (with a stage curtain and orchestra pit for opera), and a stepped ceiling is provided, designed by Thomas Futterer, based on his ray studies. These features no doubt do contribute to the provision of early lateral reflections. (The details of their design were developed by the French scenographer Jacques Tourane).

Although there are MORE steps here than in the Berlin Hall, it appeared that they might not be sufficient to overcome the potential problems of the great width of the Nice Hall, with a stage 25 m wide. The question arose, therefore, whether we could gain more lateral reflections from the proscenium walls, which widened the room stepwise from the stage to an ultimate sidewall separation of 42 m. We estimated that the time delay would be about 80 ms for the critical seating areas in the middle of the Stalls; that is, at the limits of delay within which these reflections could be considered as "early". To give these reflections the necessary strength (comparable to what might be found in narrower halls), we had to incline the reflecting panels inward in three steps, whereby they tend to have a fucusing effect at seats on the slopes in the middle of the Stalls - Figure 5. On the other hand, these reflections must be distributed over the total length of the audience, so the side reflectors were split into three "towers" having a convex curved surface in the horizontal plane.

Since we had no opportunity for an acoustic model study of the unusual shape of this multi-purpose hall, the introduction of this new concept for lateral reflections was something of a risk. Subjectively, hand-clapping in the finished hall was satisfactory and the musicians reacted positively, but we wanted more objective data. Fortunately we were able to squeeze in, between noisy building construction and a busy rehearsal schedule, some time for recording pistol shot responses at six characteristic seats in the hall. Taking advantage of the principle of reciprocity, we fired the pistol from different seats in the hall, leaving the less mobile equipment (microphone, amplifiers and tape recorder) on the centreline of the stage near the front.

Since the reverberating stage house was empty and we were interested only in the acoustics of the auditorium at that point, we closed the fire curtain, so that the microphone was located just in front of it. Thus, each recorded impulse at the microphone was followed by a mirror impulse from the fire curtain with a very short time delay. This, however, did not disturb the subsequent analysis of the relevant reflection patterns.

The calibre of the pistol was 9 mm, which assured sufficient sound pressure level for our tests. It was even an advantage that the pistol had some directivity of its own, which replaced, in its reciprocal role, the listener, whose ears are also directional at higher frequencies. On the other hand, the omni-directivity of the microphone corresponded to a statistical averaging of the various directivity patterns of different musical instruments. The pistol was pointed towards the microphone from all the seat locations. Each shot was repeated and it was ascertained in each case that the recording system was not overloaded.

Figures 6 to 8 show (at the top) the p(t) responses at seats S2, S3 and S7, as marked in the plan of Figure 4. These response records were sent to Müller-BBM in Planegg for digitizing and evaluation by P. Geissler. We had to choose between two octave-band filtered echograms, either at 500 Hz or 1000 Hz; we preferred the 1000 Hz analysis because we expected that this would exhibit less interference distortion. Since echograms pertain to tests made in the time domain we would have preferred an analysis which provided filtering in the frequency range from 800 to 5000 Hz.

In all the diagrams (see Figure 6) the first row shows the p(t) response for the first 500 ms. The diagram in the middle shows the corresponding response for $p^2(t)$. For all the criteria which attempt to characterise the ratio of early to total energy (or late energy - after 80 ms) arriving at the ears, it is $p^2(t)$ which we have integrated over time. One of these criteria, the so-called "centre-time", t_c, is marked on the abscissa; this parameter is not limited at 80 ms and, in fact, does not have a sharp limit at all; rather it is defined as the temporal distance of the "centre of gravity" of the impulse response $p^2(t)$ after the arrival of the direct sound (regarding $p^2(t)$ as "local loading" as in mechanical engineering).

$$t_c = \int_0^\infty t\, p^2(t)\, dt \Big/ \int_0^\infty p^2(t)\, dt. \qquad (1)$$

According to Lehmann's [8] subjective investigations, this quantity should not exceed 130 ms. In Figure 6 (Seat S2), $t_c = 104$ ms.

The last diagram on the bottom in each case attempts a representation which takes into account two different properties of our ears. First, the "inertia of hearing", the ability of the ear to integrate over several immediately successive impulses, is accounted for by a convolution with an exponential decay having a relaxation time of 35 ms. Second, the result of this convolution-integral is raised to the 1/4 power, the latter being approximately the exponent of the loudness-intensity function for stationary noises. Thus we get a quasi-subjective shot response by evaluating:

$$S(t) = \left[\int_0^t p^2(t')\, e^{-(t - t')/35\mathrm{ms}}\, dt' \right]^{1/4} \qquad (2)$$

So long as this function does not exhibit a peak following a pronounced valley, we may assume that no disturbing echo occurs.

Figure 6 shows the corresponding echograms for a seat in the middle of the 12th row of the Stalls, just in front of the first vineyard step. In a hall with a broad stage this is generally a location with an unfavourable "time delay gap" between the direct sound and strong reflections. But here the direct sound (split by the fire curtain reflection into a double impulse) is soon followed by several smaller reflections, and at the 80 ms limit by two very strong ones.

The question arises whether these pronounced reflections arrive from the ceiling or from the two proscenium towers. In the present case, we can decide this in terms of the time delays of the reflections with respect to the direct sound, which we determine from the longitudinal section and the plan. The first shows that the ceiling reflection would have a delay of only 35 ms, and thus fills the temporal region before the two strong reflections. On the other hand, the plan shows that the detour via the two towers corresponds to the two strong reflections. This is further supported by the fact that the heights of these peaks exceed that of the direct sound; this results partly from the superposition of two symmetrical tower reflections, and partly from the focusing properties of the towers.

Astonishing though it may be, that these strong reflections did not produce a disturbing echo, Thomas Fütterer, who listened to what the microphone recorded immediately next to him, did not hear an echo. But it can be taken for granted that a disturbance would have occured if no ceiling reflections were present to fill the temporal region preceding the tower reflections.

In fact, the tower reflections even contribute to the clarity, as is shown by the rather short "centre time" of only 104 ms - much shorter than the 143 ms which would correspond to a purely exponential decay associated with the measured reverberation time of 2 seconds (determined by backwards integration of the $p^2(t)$ response).

Seat S3, represented by Figure 7 is not on the centreline of the hall. Therefore the number of reflections is increased to about double. The highest peak corresponds to the nearest sidewall tower and, since the distance from the source has also increased, it appears after 60 ms. Also, the ceiling reflection appears earlier and has become relatively stronger. In spite of all these changes the "centre time" has remained about the same, at 104 ms.

Finally, consider the echograms at Seat S7, the seat furthest from the centreline and closest to the proscenium line in the Balcony, represented by Figure 8. Here the reflection from the nearby tower appears in the region of the ceiling reflections. This constellation may be the reason for the "centre time" observed here - 113 ms - despite the appearance of the strong reflections from the towers next to the opposite sidewall which appear 130 ms after the direct sound. But since we always have dense reflections preceding this peak, our quasi-subjective echogram S(t) here still shows a smooth curve. No acoustic anomaly has been noted in this seat.

The density of the sound reflections here is certainly due to the vineyard steps and their corresponding lateral reflections, though it is scarcely possible to distinguish their spatial contributions in the echograms. The Apollo Hall in Nice was the first example in which steps were raised also in the lateral direction, with quite broad reflecting surfaces, in a hexagonal arrangement.

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THE TRAPEZIUM-TERRACES ROOM

An easier subdivision of the audience than the hexagonal one, is the division of the seating area into trapezoidal terraces. It also performs better acoustically.

A trapezoidal plan for large auditoria has often been preferred by architects with the stage at the small end. It can be regarded as a sector of the antique amphitheatre, with its excellent views of the stage from every seat, combined with a minimum distance to the furthest listener for a given seat capacity, and without the need for boxes and balconies. However, the acoustical disadvantages of this arrangement, with sidewalls converging towards the stage at an angle β to the centreline, can easily be seen in the left plan of Figure 9. Sound rays arriving from the middle of the stage front S are not all reflected towards the middle of the hall. This is best demonstrated by the reflection point R_∞, defined as the point on the sidewall from which the reflected rays run parallel to the axis; at all more distant points along the sidewalls the rays diverge from the axis. If we seek the reflection point which directs the reflected rays to the rear wall on the axis, we find a point R_a rather near the stage. Thus, that part of the sidewall which provides the centreline seats with lateral sound (ie closer to the stage than R_a) is quite small. We may call this hall shape a "divergent trapezium", even if the rear wall is curved.

In contrast to this, the rectangular room (Figure 9, middle), with its parallel walls ($\beta = 0°$) exhibits a reflection point in the middle of the sidewall. Its front half (forward of R_a) provides lateral reflections for seats on the centreline and there is no limiting point beyond which the rays are directed outwards. This means not only that the reflections from the sidewalls are stronger, but also that they arrive more laterally. For sources with directivity towards the audience, this directivity is reinforced by the lateral reflections.

All these advantages are again increased when we proceed from parallel sidewalls ($\beta = 0°$) to sidewalls which converge towards the rear of the hall (Figure 9, right). We may call such a hall a "convergent trapezium". R_a has moved still further towards the rear of the sidewalls, the part of the sidewalls which contributes to lateral reflections has become larger, and the sound arrives still more laterally.

If we now extend our acoustical comparisons to consider all the rays arriving at any seat within 80 ms of the direct sound, then the difference between the energies is more pronounced in each case.

It is possible to combine the visual advantages of the divergent trapezium with the acoustic advantages of the convergent trapezium by constructing over a generally diverging seating plan (Figure 10), a vineyard-like stepwise ascending row arrangement, where the steps (a, b, c, d) provide the convergent trapezoidal surfaces, reflecting the sound rays towards the middle (E_a, E_b, E_c, E_d), thus forming a "trapezium terraces" room.

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By projecting a ray obliquely on plan (Figure 10, bottom) from S at the centre front of stage, it is easy to see that, due to the vertical projections at steps "a, b, c" and the convergent part of the sidewall "d", these rays can provide early lateral reflections, not only to the rear Stalls but also to each successive terrace. In each case, the R´ points in plan (Figure 10, bottom) are simply vertical lines in the longitudinal section (Figure 10, top), whereas the heights for source and receiver are fixed: E at seated head height and S at sitting or standing head height. The rules governing the seating rake are regarded as already well known.

If the surfaces of "a" to "d" are always vertical, the ray would ascend after reflection at the same angle in longitudinal section as before reflection; it would be a straight line from S to E in section, which would also determine the reflection point. But this point would be effective only if it lies on the corresponding step and if the rays are not grazing other heads. In the Stalls this may be safely assumed, if the rake is not (as usual) steeper than necessary; i.e. it has a concave, progressive profile, where the angle between the sightline to the higher placed performer and that to the person seated in the next row, remains the same. In the higher terraces this more difficult construction would not be worthwhile.

In the higher terraces we can no longer assume that a suitable reflection point is available on the straight line between source and receiver in section. To be effective this point must be higher on the plane R´. This means that the ray from source to receiver also shows a deviation in long section which can be produced by a forward inclination of the corresponding step. The required inclination may easily be found by rotating a mirror in a light-ray-model. Under the conditions of Figure 10 the angle of declination amounts to about 20°.

It remains to check, in plan and section, whether these lateral reflections exceed the 80 ms limit. In general this is unlikely; in the Stalls because of the short distance to the first step, and in the higher Terraces because of the increasing length of the direct path.

The "trapezium terrace" room offers the chance to use all parts of the lateral walls for early lateral reflections, equally distributed to all the seats.

The question arises whether directing too much energy from first reflections onto the absorptive audience may deplete the required late, statistically-distributed, reverberant sound. At low frequencies, and generally at mid-frequencies, this is unlikely because specular reflections from a step with limited free height can occur only above a certain limiting frequency. It is only the high-frequency energy which would be diverted from the reverberation by panel reflections; the low frequencies, which convey "warmth", would be unaffected, whereas clarity and the perception of early lateral reflections, is best at wavelengths which are short with respect to the inter-aural distance.

Properly speaking, a new concept for an auditorium should be recommended only if some practical experience with it exists. Fortunately, we are at least able to show architectural drawings for such an auditorium. For a multi-purpose, 2500 seat concert/congress hall in Las Palmas in the Grand Canary Islands in Spain,

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the architect Oscar Tusquets and his associates (Barcelona) chose a divergent trapezium for the ground plan. Based on earlier collaboration with me on another project, and even before asking for my acoustical assistance, they divided the audience area by means of "vineyard steps", corresponding to convergent trapezia. In this case I could not possible have found more ideal conditions for the realization of my concept of the trapezium terrace room! I had only to make proposals for acoustical optimizing of the steps.

The result is seen in Figure 11. The angle β is even greater than I had proposed for another project and the design is more progressive.

If the auditorium is also to be used for drama and for opera, we must avoid distances which are too great to seats on the highest terraces. Therefore we should let the terraces overlap, balcony-like, but at most only two rows on the side and four rows at the rear wall. In these cases the "cornice" reflections from the soffits and the vertical walls can produce the desired early lateral reflections. Figure 12 shows a photograph of the audience of a multipurpose hall in Ljubljana (Yugoslavia) seating 1600 designed by the architect Ravnikar, with acoustical consultation by Oskar Gerber and me [9].

I hope that I have been able to make clear, with these architecturally quite different examples for the provision of early lateral reflections, that we are not forced for this purpose to copy some special hall shape, such as the shoebox shape of the late nineteenth century.

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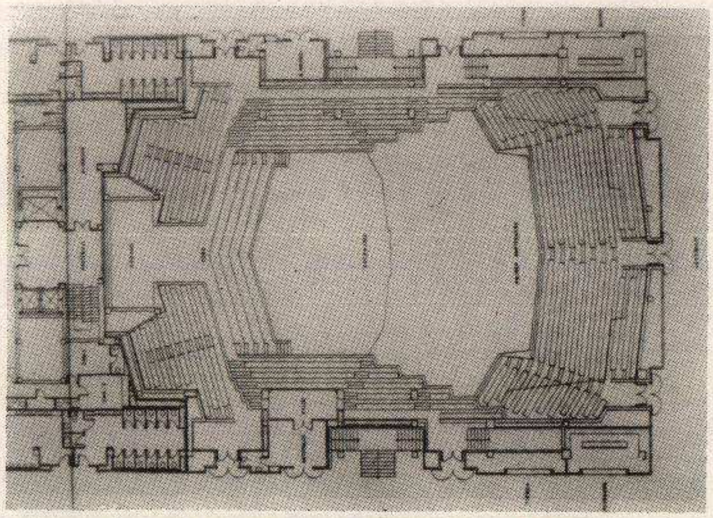

Fig. 1 Plan of the Auditorio National in Madrid (Arch: Garcia de Paredes).

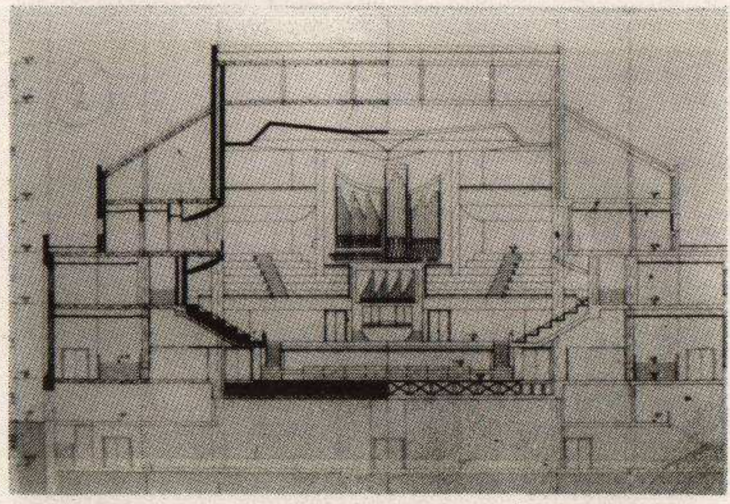

Fig. 2 Cross-section of the Auditorio National in Madrid.

The Apollo Hall in Nice
(Arch: Buzzi, Baptiste and Bernasconi).

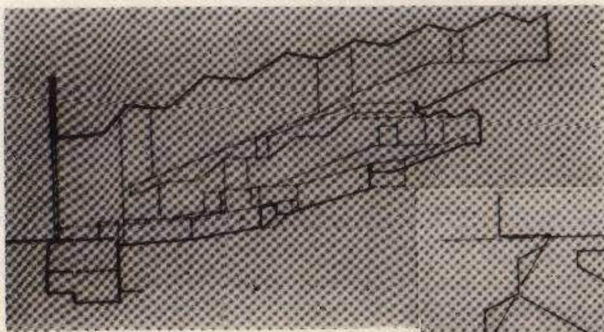

Fig.3 Longitudinal section

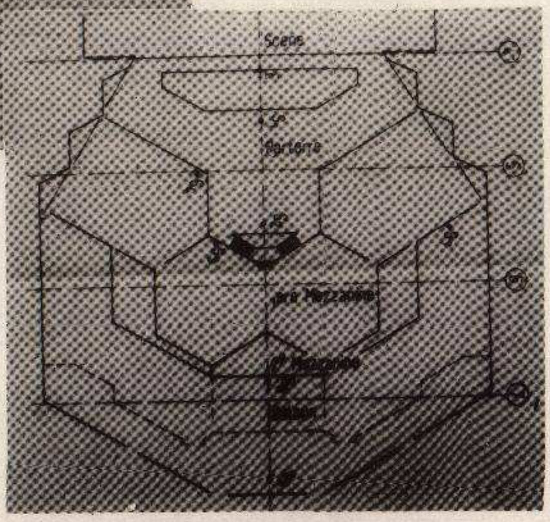

Fig. 4 Plan

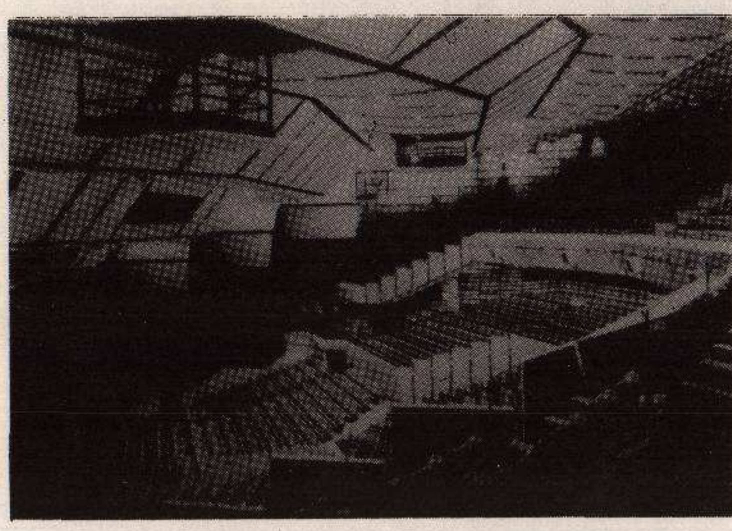

Fig. 5 View towards the "proscenium towers".

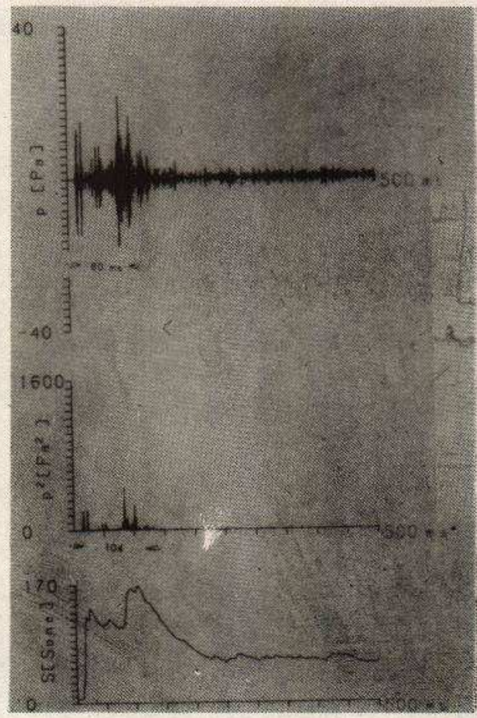

Fig. 6 Seat S2

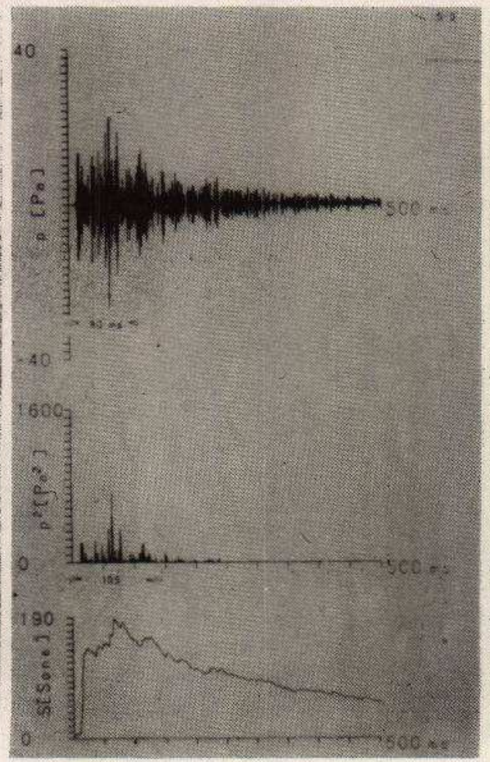

Fig. 7 Seat S3

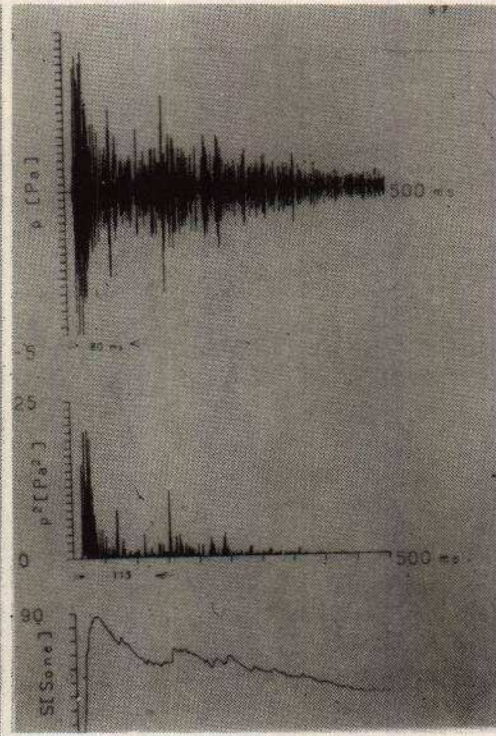

Fig. 8 Seat S7

Echograms at seats S2, S3 and S7 in the Apollo Hall in Nice.

Top:	p(t)
Middle:	$p^2(t)$ with "centre-time", t_c, indicated on the abscissa
Bottom:	quasi-subjective response S(t).

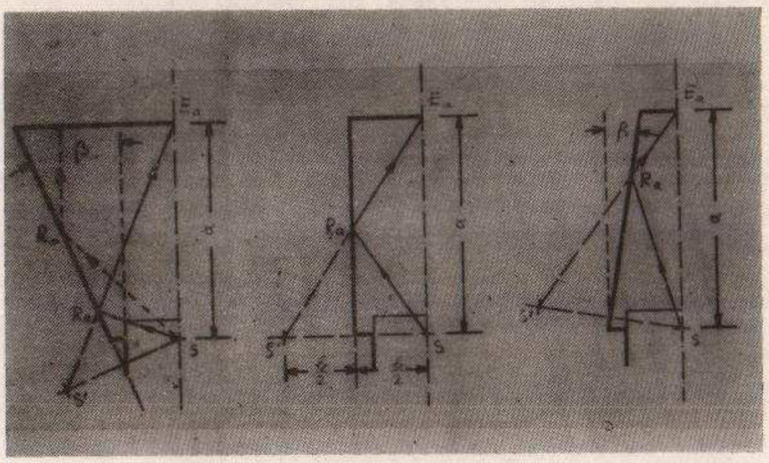

Fig. 9 Comparison between later reflections in different plan forms, each with the same stage width (bottom):
left - a divergent trapezium
middle - a rectangle
right - a convergent trapezium.

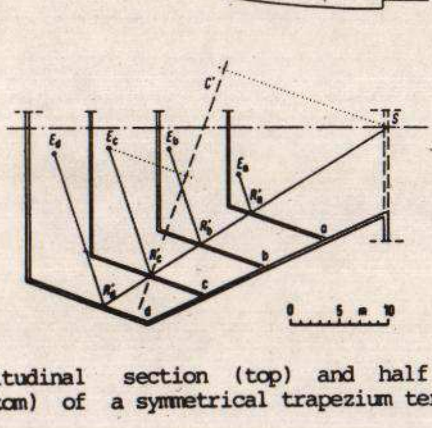

Fig. 10 Longitudinal section (top) and half plan (bottom) of a symmetrical trapezium terraces room.

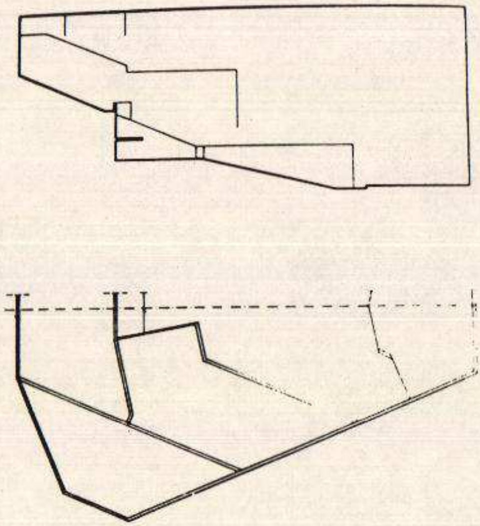

Fig. 11 Longitudinal section (top) and half the symmetrical plan of the Las Palmas hall (Arch: Oscar Tusquets).

Fig. 12 View towards the audience in the multipurpose hall of Ljubljana (Arch: Ravnikar).