Introducing the surface diffusion and edge scattering in a pyramid-tracing numerical model for room acoustics

Angelo Farina

Dipartimento di Ingegneria Industriale, Università di Parma
Via delle Scienze - 43100 PARMA - tel. +39 0521 905854 - fax +39 0521 905705
E-MAIL: farina@pcfarina.eng.unipr.it - HTTP://pcfarina.eng.unipr.it

Abstract

Surface diffusion and edge scattering are wavy phenomena which are usually badly reproduced by room acoustics software, based on geometrical acoustics assumptions. This paper presents some recent improvements to the Pyramid Tracing algorithm, which take into account the scattering of sound from the edges of finite-size surfaces, and the surface diffusion coefficient (as defined and measured in a parallel paper).

1. Precis

Moving from the definition of a new, physically-based "diffusion coefficient", as reported in a parallel paper, in this work it is described how it is possible to implement this concept inside a well-known room acoustic numerical model, based on the Pyramid Tracing approach. The modified algorithm does not suffer of increased computation time, because it was possible to maintain a single geometrical tracing, covering simultaneously 10 octave bands.

In practice, the diffusion coefficient is taken into account as follows: when a pyramid hits a surface with (frequency-dependant) diffusion coefficient greater than zero, an amount of the reflected energy (correspondent to the diffusion coefficient value) is converted from the "specular energy" container to the "diffuse energy" container. Thereafter, the remaining specular energy is applied only to the receivers inscribed within the pyramid boundaries, whilst the diffuse energy is applied to all the receivers in front of the surface hit. The propagation algorithm takes into account properly for the total path of the pyramid, from the virtual source position to each receivers, and compensates for the geometrical spreading of the diffused energy over a 2π steradians solid angle.

Furthermore, the edge diffraction effect was also better taken into account: previously this was considered only for receivers shielded behind obstructing surfaces, now the edge contribution is computed also for receivers which are not shielded. This is obtained making the diffusion coefficient to increase when the pyramid axis hits near the boundary of a face. The value of the diffusion coefficient is made to vary linearly from the original value for the central part of the surface (at $\lambda/2$ from the edge) up to 1 (at the edge).

The combination of these improvements made it possible to obtain numerical simulations in close agreement with the experimental results (which are presented in a parallel paper). In particular, the numerical model was employed for obtaining a large number of impulse responses, for receivers placed at little distance each other along a straight line. The Wave Field Synthesis theory was applied for comparing the numerical results with the experimental ones, and it was found that, when the proper value for the diffusion coefficient is employed, the discrepancies are below the measurement error.

2. Introduction

In a parallel paper [1] the definition of a measurable diffusion coefficient is investigated. It was concluded that the actual proposal being circulated in the AES-Standards SC-04 [2,3] is a robust, realistic measurement of the scattering **uniformity**, and thus is a good descriptor of the comparative quality of different diffusers: this is certainly the primary point for manufacturers of diffusing panels. But it was also concluded that such an uniformity descriptor does not correspond with the quantity usually employed in room-acoustics simulation software.

The basis of most room acoustics software is a simplified propagation theory, usually known as “geometrical acoustics”: under this theory, the sound propagates along straight paths (“sound rays”) with constant speed, and bounces over delimiting surfaces obeying to the specular reflection Snell’s law. In most cases, only flat surfaces are considered, and curved surfaces are approximated with many, little flat segments. In such a scheme, wavy phenomena such as diffraction, interference and diffusion are not correctly modeled, although their macroscopic effect can be added through various corrective techniques.

The first important distinction, which needs to be made, is the separation between edge scattering and surface diffusion. In practice, these two things are not always well separated, because often diffusing surfaces are made of many smaller ones, presenting a lot of edges, so that it is not clear if the diffusion of sound is caused by the surfaces or by their edges. And the diffusion uniformity coefficient suggested in [2,3] does not make any separation between them.

But, under the geometrical acoustics assumptions, a flat, polished surface can only cause specular reflections, and diffusion can occur only at its edges, and only if at the edge a sort of discontinuity is present (i.e., a free edge). When a large surface, such as a wall or a ceiling, presents an uneven surface, usually this is not modeled drawing each little detail of the surface itself, because the geometrical acoustics assumptions require that each surface is large compared to the wavelength. Instead, the surface is drawn flat, but a “diffusion coefficient” is assigned to it, for instructing the program to take into account, in some way, of the capability of the real structure to redirect the sound in directions different from the one described by the Snell’s law.

In these terms, the diffusion coefficient is a property which relates to an uniform, theoretically infinite surface, with no reference to the edge effects.

On the other hand it is of experimental evidence, as shown in [1], that the free edges of a perfectly flat and polished surface are the locus of redirection of a relevant part of the reflected sound. This redirected energy seems to originate from local sound sources located exactly on the edge of the panel, instead of from a virtual sound source located well behind the panel, as it happens for the specularly reflected energy. So, independently from the possible presence of a surface diffusion effect in the middle of the surface, there is always an edge effect to take into account.

If a numerical model of the edge effect was good enough, drawing all the geometrical details of a rough surface would produce a realistic simulation of the sound energy reflected back from it, in any direction. In practice, the strong simplifications inherent with the geometrical acoustics approach makes this goal unrealizable, at least until we do not decide to forget the geometrical acoustics limitations, and to move to a true wave simulation, for example thanks to a Boundary Element formulation.

So the theoretical scenario in which we are moving is a typical geometrical acoustics model, with added the surface diffusion effect and the edge effect. Both these effects are in general frequency-dependent: this means that the diffusion coefficient δ has a different value at each frequency, and similarly the edge proximity has to be evaluated in comparison with the wavelength.

3. Theoretical formulation of the diffusion coefficient

In most room acoustics computer programs [4,5], and also in the pyramid tracing approach discussed here [6], the diffusion coefficient δ is defined as the ratio between the energy reflected in a diffuse way and the total reflected energy. Going in more detail, the reflected energy has to be separated in a specular part and in a diffuse part. Fig. 1 illustrates the conceptual scheme of this separation.

The specular part is the one which seems to originate by a virtual image source, obtained by the specular reflection of the true source on the "mirror" constituted by the surface. If the surface is of finite size, this energy only flows within a sort of pyramid, defined by the virtual image source as vertex and the reflecting surface as base. Only receivers located within the prosecution of this pyramid (under its base) will receive the specular energy, which can be computed as:

$$I_{spec} = \frac{W \cdot Q_{\vartheta}}{4 \cdot \pi \cdot (r_1 + r_2)^2} \cdot (1-\alpha) \cdot (1-\delta) \tag{1}$$

In this formula the following notations were used:
Ispec is the sound intensity (W/m^2) which arrives at the receivers located within the above defined pyramid,

- W is the total power radiated from the point source (in Watts),
- Q_θ is the directivity factor in the direction along which the sound was radiated toward the reflecting surface,
- r_1 is the distance between the sound source and the reflecting surface, in m
- r_2 is the distance between the reflecting surface and the receiver, in m
- α is the absorption coefficient of the surface (usually not considered angle-dependent)
- δ is the diffusion coefficient of the surface (usually not considered angle-dependent)

Another part of the total reflected energy is re-irradiated in a diffuse way. This can be seen as the radiation of many, little sources, placed on the whole surface, each of them redirecting the energy which was impinging on a small surface element having area dA. All these elementary sources contribute to the energy which arrives at a receiver (located everywhere in the hemispace in front of the reflecting surface), following this equation:

$$I_{diff} = \int_A \frac{W \cdot Q_{\vartheta}}{4 \cdot \pi \cdot r_1^2} \cdot \cos(\varphi_1) \cdot \frac{(1-\alpha) \cdot \delta}{2 \cdot \pi \cdot r_2^2} \cdot Q_{\varphi_2} \cdot dA \tag{2}$$

In which these new symbols were used:

- φ_1 is the angle between the local normal to the surface and the ray arriving from the sound source (which is long r_1 m),
- φ_2 is the angle between the local normal to the surface and the ray going to the receiver (which is long r_2 m),
- $Q_{\varphi 2}$ is the radiation directivity in direction φ_2. It can be taken constant and equal to 1 (uniform diffusion), or varying with $2 \cdot \cos(\varphi_2)$ (Lambert's law),
- A is the total area of the reflecting surface in m^2.

It can be noted that $W \cdot (1-\alpha) \cdot \delta$ can be taken out of the integral. In most cases, the single energy contributions are not directly summed, as the model takes into account the travel time, and stores separately each energy arrival as function of the travel time, for the construction of the energetic impulse response.

Obviously, the implementation of the previous equation is too complex for being employed in a fast numerical model, and thus it has to be simplified.

The method described here is based on the "pyramid tracing" scheme, which was already described in detail by the author in [6,7,8]. In substance, as shown in fig. 2, the radiation from the sound source is subdivided in a large number (N_{pyr}) of triangular beams, each having the same solid angle (although not always the same exact shape). So, the discretisation of the small area elements dA can be seen as the subdivision of the surface A in the triangles obtained by intersection with the pyramids launched from the source, as depicted in fig. 2.

Each pyramid which hits the reflecting surface cause a single energy contribution to each receiver "seen" in the hemispace in front of the surface. A first approach for computing this individual contribution can be obtained assuming uniform diffusion ($Q_{\varphi 2}=1$) and observing that the elementary area element $dA \cdot \cos(\varphi_1)$ is given simply by $4 \cdot \pi \cdot r_1^2 / N_{pyr}$; this yields to:

$$I_{diff} = \frac{W \cdot Q_{\vartheta}}{N_{pyr}} \cdot \frac{(1-\alpha) \cdot \delta}{2 \cdot \pi \cdot r_2^2} \tag{3}$$

This produces correct results only if the receiver is far from the reflecting surface. If instead the receiver is very close to the reflecting surface, the finite meshing of it and the fact that the re-irradiated diffuse energy is assumed to come out from a single point source at the center of the area element can cause intolerable artifacts. In fact, if the value of r_2 is very little, it can well happen that the diffuse intensity I_{diff} becomes greater than the incident intensity:

$$I_{inc} = \frac{W \cdot Q_{\vartheta}}{4 \cdot \pi \cdot r_1^2} \tag{4}$$

Obviously this is a paradox. For avoiding it, it is necessary to dilute the re-irradiated energy over the area of the elementary surface defined by the intersection of the pyramid with the reflecting surface. This suggests the following formulation:

$$I_{diff} = \frac{W \cdot Q_{\vartheta} \cdot (1-\alpha) \cdot \delta}{4 \cdot \pi \cdot r_1^2 + N_{pyr} \cdot 2 \cdot \pi \cdot r_2^2} \tag{5}$$

Which substantially comes back to the previous one when r_2 is very large, but reduces to the diffuse intensity on the surface as r_2 goes to zero.

Now the edge effect will be taken into account. It must be evidenced that the edge effect was already included in the original Pyramid Tracing formulation, but only for those receivers which were shielded behind an obstructing surface [6,7]. This was implemented through the Kurze formulation [9]. This approach is not satisfying for the receivers which are in the hemispace facing the reflecting surface, so another method was added.

In practice, when a pyramid hits a surface near an edge, the local value of the diffusion coefficient δ is increased towards 1. This begins to happen at a distance of $\lambda/2$ from the edge, and the increase of the diffusion coefficient is linear starting from the original value δ_0 (valid for the central region of the surface, far from the edges). The following equation was employed for recomputing the local value of δ, as function of the distance e from the edge:

$$\delta = \delta_0 + (1-\delta_0)\cdot\left(1-\frac{e}{\lambda/2}\right) \tag{6}$$

4. Extension to higher-order reflections

The formulation presented here holds at this point only for the first reflection. The extension to multiple reflections introduces further problems, so that some room acoustic programs limit the accurate treatment of diffusion only to first or second order reflections, therefore switching to a more simplified diffusion approximation. Widely used approaches are the randomization of the direction of the specularly-reflected energy and the hybridization with a statistical treatment of the reverberant tail.

In the first approach, first a random number, bounded between 0 and 1, is generated at each reflection: if the value is higher than the diffusion coefficient δ, then the reflection is computed specularly, following the Snell's law. If instead the random number is lower or equal to δ, a new direction for the reflected energy is randomly generated, perhaps taking into account a probability distribution corresponding to the Lambert's law. This approach is very effective for pure ray tracing methods, but it can work also with diverging beam tracers, provided that a reasonably high number of beams is generated. In any case, this method causes the program to behave in a MonteCarlo way, exhibiting statistical convergence to stable results only by increasing the number of beams. Another defect is that, for taking into account the dependence of δ with the frequency, it is necessary to repeat the whole calculations for each frequency band.

In the second approach, at each reflection a part of the energy associated with the ray (or beam) is stripped away, and goes to a common energy repository. Of course, the stripped energy is the product of δ and the total reflected energy after the reflection; the remaining (1-δ) fraction of the reflected energy prosecutes the specular propagation. After the computation is prosecuted and terminated in a deterministic way for the survived specular energy, the whole amount of energy stored in the "diffuse repository" is employed for computing a statistical reverberant tail, which is added to the specular one, following consolidated statistical theories such as Sabine or Eyring. This approach is clever and satisfying, but it has the defect to rely on statistical assumptions which holds only for regular spaces, and is not well suited to the study of "strange" rooms such as workshops, tunnels, and so on.

For overcoming the limits connected with actually employed schemes, but maintaining complete coherence with the general assumptions of the Pyramid Tracing implementation known as Ramsete [6,7,8], a new multiple diffusion model was developed.

First, it is necessary to remind that in the original (diffusion-less) implementation the program was employing a not-hybrid approach, following each pyramid for its whole history, and avoiding carefully to superimpose any reverberant tail coming from statistical theories. Furthermore, the computation was made simultaneously in 10 octave bands, with a single geometrical simulation: this caused the program to be much faster than the others who had to repeat the ray tracing for each frequency.

These features were considered very important also after introducing the diffusion model. So the new approach was to maintain the tracing of each pyramid for its whole history, but recomputing at each reflection the amount of "specular" and "diffuse" energy associated with that pyramid. No "common diffuse repository" was defined.

In practice, each pyramid always starts with the whole energy assigned to be "specular", and without any "diffuse" energy (although it is straightforward to implement an extension of the algorithm allowing for "diffuse" sound sources, such as Distributed-Mode Loudspeakers [10]). At each reflection, a fraction of the reflected energy proportional to δ is passed to the "diffuse" container, whilst the remaining energy remains "specular". This can be easily implemented maintaining a single energy value associated with the pyramid, but computing an incremental total diffusion coefficient δ_{tot} after each reflection, as function of the previous value of δ_{tot} and the new value of δ of the actual reflection:

$$\delta_{tot} = \delta_{tot} + (1-\delta_{tot}) \cdot \delta \tag{7}$$

After this, any higher-order reflection can be treated as a first-order one, employing eqn. (1) and (5) for computing the intensity received within the pyramid (specular) and everywhere (diffuse). In doing that, we must account for the multiple reflections: thus, in place of (1-α), we have to consider the product of all the (1-α) values encountered at each reflection, and r_1 is in this case the total path $r_{1tot}$from the original sound source to the last reflection point. So these two equations can be re-written as:

$$I_{spec} = \frac{W \cdot Q_{\vartheta}}{4 \cdot \pi \cdot (r_{1tot} + r_2)^2} \cdot \left[\prod_{i=1}^{N} (1-\alpha_i) \right] \cdot (1-\delta_{tot}) \tag{8}$$

$$I_{diff} = \frac{W \cdot Q_{\vartheta} \cdot \left[\prod_{i=1}^{N} (1-\alpha_i) \right] \cdot \delta_{tot}}{4 \cdot \pi \cdot {r_{1tot}}^2 + N_{pyr} \cdot 2 \cdot \pi \cdot {r_2}^2} \tag{9}$$

It must be noted that a receiver located within the pyramid will receive both these intensities. After a long path (in the late part of the reverberant tail), the value of δ_{tot} is almost 1, and the pyramid base is so huge that all the receivers are always within it. So in practice the received intensity comes back to the same value which was computed by the previous, diffuse-less version of the program.

The introduction of the diffusion algorithms produces relevant modification only of the early part of the computed impulse response, as the first reflections, which previously resulted as isolated sharp peaks, are now followed by small diffuse tails, and this makes the simulation to look (and sound) much more realistic.

This means that also the original diffusion-less formulation of the Pyramid Tracing algorithm produced in practice a diffuse reverberant tail, but in that case the progressive transition between the first part of the echogram (deterministic and specular), and the second part (statistical and diffuse) was governed by the value of the critical time t_c:

$$t_c = \sqrt{\frac{lcm^2 \cdot N_{pyr}}{4 \cdot c_0^2 \cdot \beta}} \tag{10}$$

As shown, t_c depends from the mean free path lcm and from the adimensional shape factor β, which are invariant for a given geometrical case, but also from the number of pyramids N_{pyr}. This explains why, for each case, there was an "optimal" number of pyramids, and when this was exceeded, the simulation accuracy tended to reduce instead of improving.

With the new formulation, the transition between the specular and diffuse behavior is no more governed by the number of pyramids, because eqn 9 compensates for it. Instead, the transition depends on the rapidity with which the running incremental diffusion coefficient δ_{tot} approaches 1, and this is affected by the values of the diffusion coefficient of the surfaces hit, but also on the number of edges which are included in the geometry under test.

5. Experimental verification

As the new diffusion algorithm is running, at the time of writing, only since a couple of months, it was not possible to conduct a large-scale validation experiment yet. Here only a simple comparison with the experimental results presented in [1] will be presented.

Fig. 3 shows the geometrical CAD model of the case under test, which closely correspond to the laboratory setup described in [1]: a loudspeaker is mounted flush in the floor (so that we can disregard completely the presence of the floor itself), and a diffusing panel is suspended above it. 255 microphone positions are considered, along a straight line passing horizontally, midway between the loudspeaker and the panel, and an highly-detailed impulse response is recorded at each microphone (time resolution is approximately 66 μs).

This geometrical setup allows for the employ of the mathematical processing tools known as Wave Field Synthesis [11], which makes it easy to recompute the sound field in other (virtual) positions starting from the measured (or computed) data along the straight line. This feature was employed for the computation of the reflected energy over a circular arch, as it is required for the evaluation of the "diffusion uniformity coefficient" described in [2,3].

Four cases were modeled: a flat, polished panel (no surface diffusion, only edge effects), an highly diffusing flat panel (a Schroeder-type diffuser) and a curved, polished surface both in the direction of maximum diffusion and of minimum diffusion (rotated 90°).

The experimental results of the same four cases are presented in [1]. Figs 4, 5, and 6 show the results of the numerical simulations obtained with Ramsete-II (pyramid tracing with diffusion) at 1 kHz of the first three panels. For checking the similitude of the numerical and experimental results in a quantitative way, a sort of "pattern-matching" between the images was attempted. In practice, each image is a matrix, having 255 columns and 400 rows (26 ms), and each cell contains a sound intensity (in W/m^2). So it is possible to compute an RMS percentage error, and express it in dB, with the following expression:

$$E = 10 \cdot \lg \left[\sqrt{ \frac{ \sum_{i=1}^{N} \left(I_{sper,i} - I_{num,i} \right)^2 }{ \sum_{i=1}^{N} \left(I_{sper,i} \right)^2 } } \right] \tag{11}$$

This value is an indicator of the simulation's error in comparison with the experimental result, and can be assimilated to a sort of a Noise-to-Signal ratio.

Each simulation was repeated 3 times, with different values of the diffusion coefficient δ: in the first case it was assumed to be zero (diffusion-less), in the second case it was set equal to the newly-defined quantitative diffusion coefficient δ_{opt}, derived in [1] from the experimental results, and in the third case it was set equal to the "diffusion uniformity coefficient” δ_{uc}, defined in [2,3] and also computed in [1] from the experimental results. The following table presents the obtained results, in terms of the average error E:

Values of the percentage error, in dB, between numerical and experimental results

Parameter	Flat Panel	Galav2 diffuser	curved panel	curved panel (90°)
α	0	0.03	0.286	0.76
δ	0.117	0.86	1	0.20
δ_{uc}	0.35	0.86	0.92	0.52
E_0	-4.12	+3.45	+1.70	-3.99
E_δ	-4.28	-4.75	-6.42	-4.71
$E_{\delta uc}$	-3.73	-4.75	-5.21	-4.33

It can be seen how the error is slightly reduced when the new quantitative diffusion coefficient δ is employed, although the use of the qualitative coefficient δ_{uc} is usually better than neglecting completely the diffusion.

Looking at fig. 6, anyway, it is evident that modeling a curved diffuser as a flat surface produces a simulated sound field very different from the experimental one. This is due to the fact that a diffuse tail is produced, whilst in practice the reflected sound is always a sharp peak. Repeating the simulation, but having actually designed the true shape of the surface, and assigning to it a diffusion coefficient = 0, produces a more realistic simulation of a curved surface, as it is clearly shown in fig. 7.

It remains to check how the sound of the simulated reflections resembles the experimental one, in terms of auditory perception.

6. Conclusions

From the results obtained, it can be concluded that the quantitative diffusion coefficient defined in par. 3 and employed in the Pyramid Tracing program Ramsete II, as in many other room acoustics programs, is definitely a different quantity from the “diffusion uniformity coefficient” recently proposed [2,3]. Nevertheless, if the proper value for the diffusion coefficient is employed, today’s numerical models provide a reasonably good emulation of the diffusion phenomena.

The problem thus moves again to the experimental measurement of the diffusion coefficient, so that huge data-bases of diffusion coefficient values can be filled and distributed with room acoustics programs. In the meanwhile, most values of δ employed in room acoustics simulations will be simply invented, and in the only cases in which some experimental data is made available from the producers of commercial diffusors, probably these will be in the form of the diffusion uniformity coefficient, which can cause significant errors if employed in place of the “true” diffusion coefficient.

This research will prosecute, in parallel with the experimental measurements already scheduled [1], with the goal to obtain the optimal values of the diffusion coefficient δ_{opt} which reduces to a minimum the discrepancy between numerical and experimental results. Although this way of deriving the actual values of the diffusion coefficient could appear inelegant and antiscientific, it must be noted that this approach is substantially the same employed for the estimate of the Sabine’s absorption coefficient: this is defined as the value of α which makes the theoretical model (the Sabine's equation) to maximally match with the experimental results.

And, from a practical point of view, what is needed is simply to know the "right" values of the diffusion coefficient to assign, at each frequency, to various materials, so that our actual room acoustics numerical models produce substantially correct results.

7. Acknowledgements

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8. References

[1] A. Farina, E. Crema, M. Zanolin, "Measurement of sound scattering properties of diffusing panels through the Wave Field Synthesis approach", Pre-prints of the 108th AES Convention, Paris, 19-22 February 2000.

[2] T.J. Hargreaves, T.J. Cox, Y.W. Lam, P. D'Antonio, "Characterising scattering from room surfaces", proc. 16th ICA and 135th Meeting A.S.A., Seattle WA, vol. IV, pp2731-2732, June 1998.

[3] P. D' Antonio, T. Cox, "Two Decades of Sound Diffusor Design and Development" (part 1 and 2) Journal of AES vol. 46, n° 12 (December 1998).

[4] Naylor G.M. - "ODEON - Another Hybrid Room Acoustical Model" - Applied Acoustics Vol. 38 no.s 2-4, pag. 131 (1993).

[5] Verification of Prediction Based on Randomized Tail-Corrected Cone-Tracing and Array Modeling, B.-I. Dalenbäck, 137th ASA/2nd EAA Berlin (March 1999);

[6] A. Farina - "RAMSETE - a new Pyramid Tracer for medium and large scale acoustic problems" - Euro-Noise 95 Conference, Lyon 21-23 march 1995.

[7] A. Farina - "Pyramid Tracing vs. Ray Tracing for the simulation of sound propagation in large rooms" - In the volume "Computational Acoustics and its Environmental Applications", pp. 109-116, Editor C.A. Brebbia, Computational Mechanics Publications, Southampton (GB) 1995.

[8] A. Farina - "Verification of the accuracy of the Pyramid Tracing algorithm by comparison with experimental measurements by objective parameters" - ICA95 (International Conference on Acoustics), Trondheim (Norway) 26-30 June 1995.

[9] Kurze, U.J., "Noise Reduction by Barriers", Journ. of Ac. Soc. America, vol. 55 (1974), pp. 504-518.

[10] Gontcharov V. P., N. P. R. Hill,V. J. Taylor, "Measurement Aspects of Distributed Mode Loudspeakers" - Pre-prints of the 106th Convention, Munich, Germany, 1999 May 8–11 #4970

[11] A. J. Berkhout, P. Vogel, D. de Vries, "Use of Wave Field Synthesis for Natural Reinforced Sound" – Pre-prints of the 92th AES Convention, #3299, March 1992

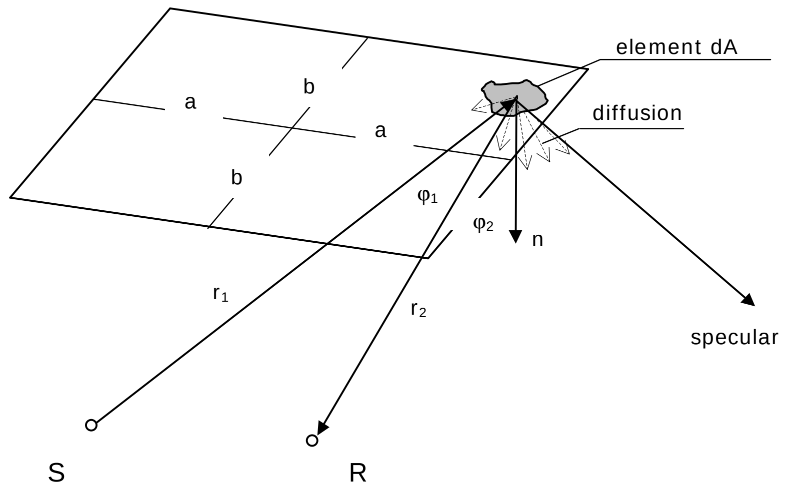

Fig. 1 – Scheme of the separation of reflected energy into diffuse and specular

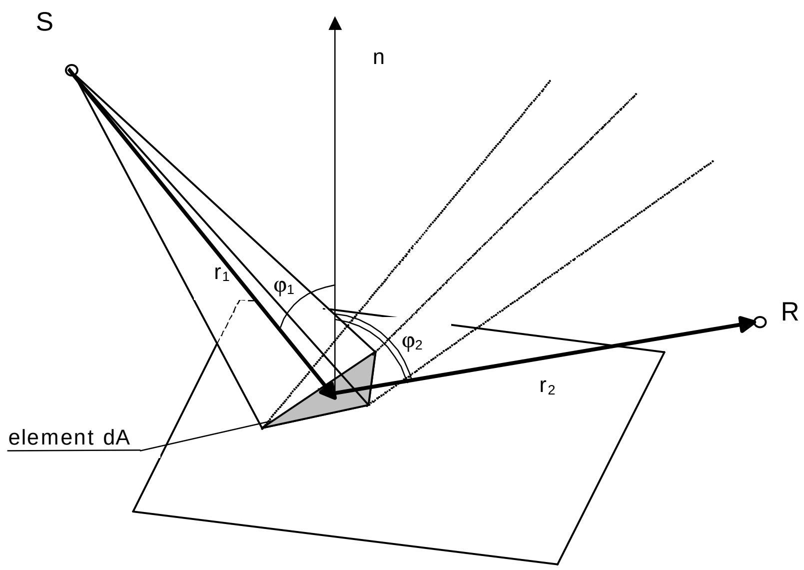

Fig. 2 – a pyramid impacting over a reflecting surface

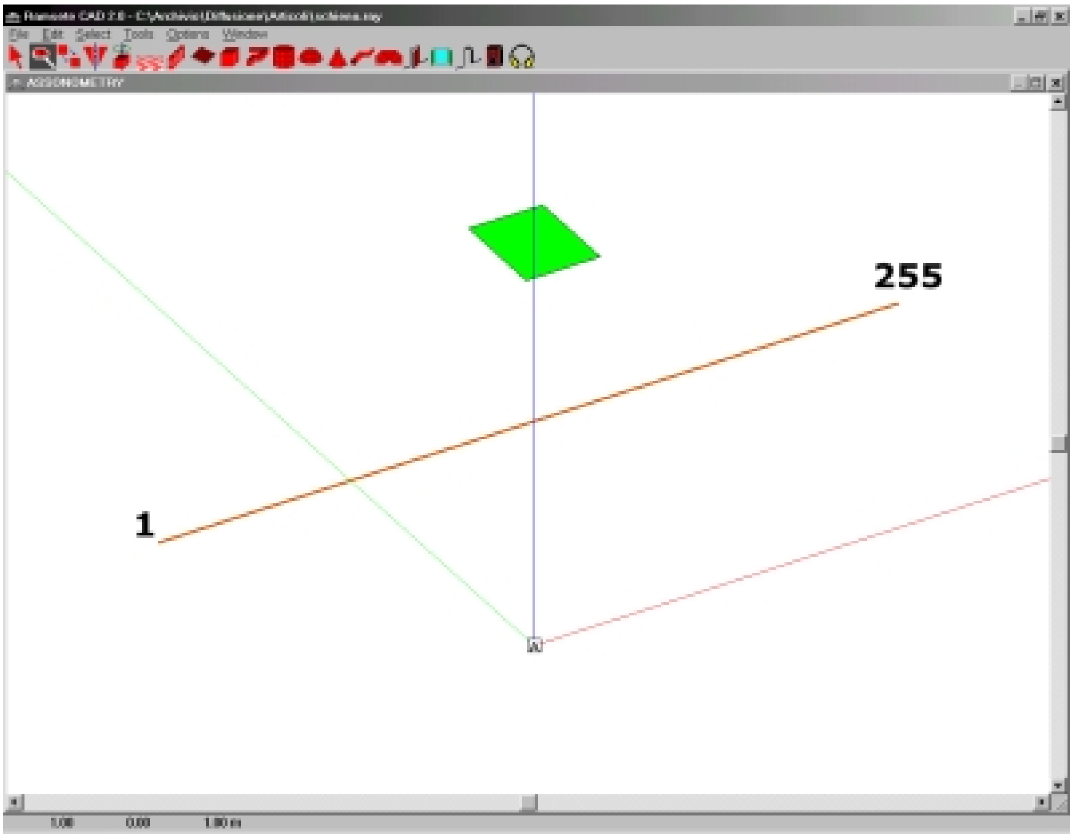

Fig. 3 – CAD representation of the measurement setup

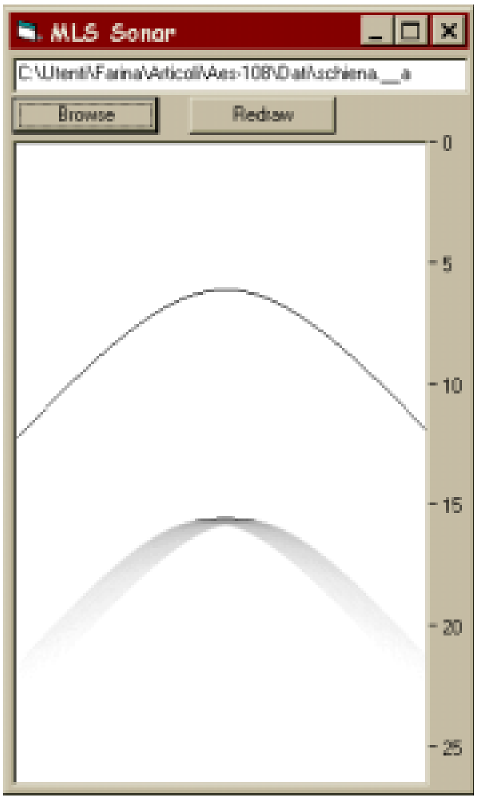

Fig. 4 – numerical simulation of the diffusion from a flat, square panel (δ=0.117)

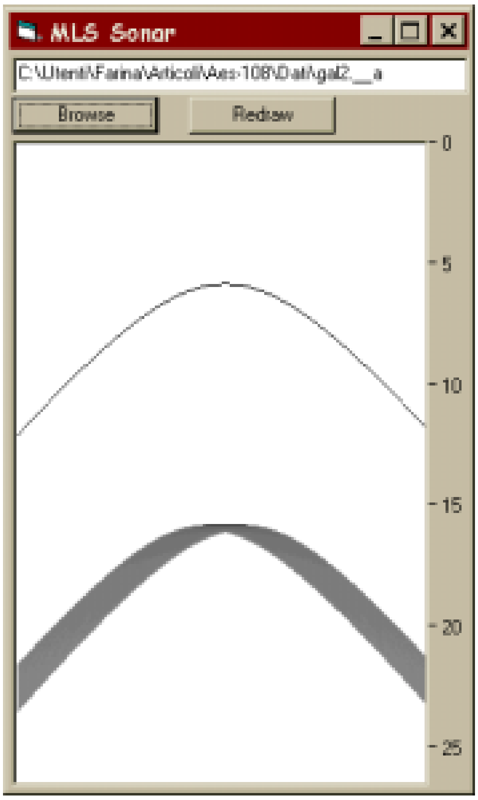

Fig. 5 – numerical simulation of the diffusion from a square diffuser (δ=0.86)

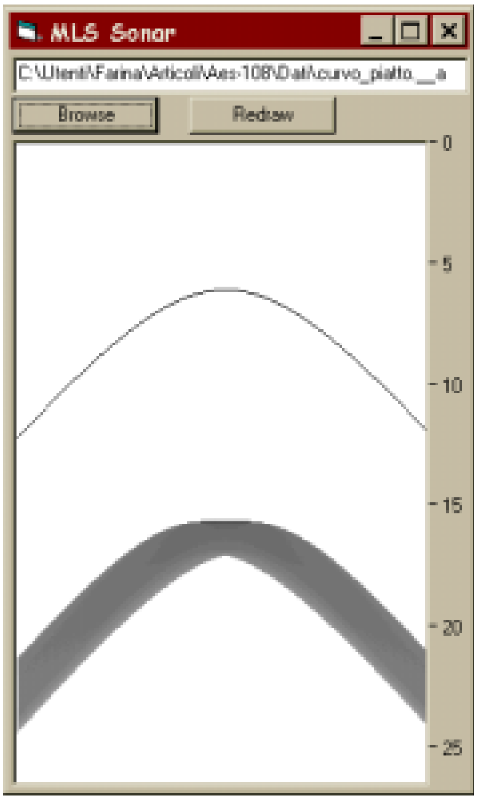

Fig. 5 – numerical simulation of the diffusion from a curved surface, modeled as a flat panel with high diffusion coefficient (δ=1)

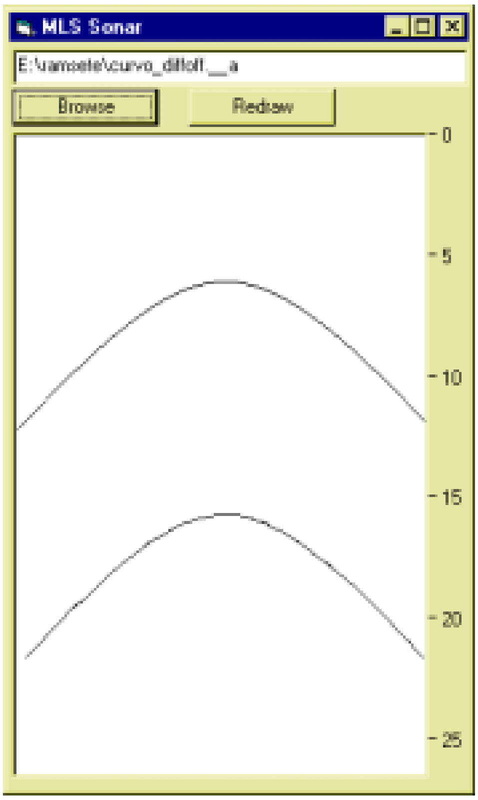

Fig. 6 - numerical simulation of the diffusion from a curved surface, modeled as a curved panel without diffusion coefficient (δ=0)