

# Whitepaper: What is Geometrical Acoustics (GA)?

Generic version without links to *CATT-Acoustic* documentation, the full version is included with the software

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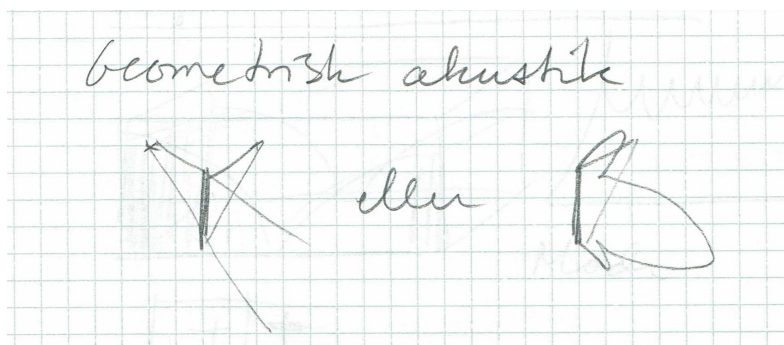
## 1. Introduction

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The widespread use of room acoustics and/or sound system prediction software based on, or mainly on, geometrical acoustics has made it necessary to revisit and expand on what GA actually means and especially discuss its fundamental limitations. It appears that it no longer always is a part of all education in room acoustics, not even when a GA-based software is used in courses, or at the very least it is not sufficiently stressed what it means. A problem is that there is no common single definition of what GA is and many times GA-based software include wave-based extensions such as early edge diffraction or direct sound interference and the development of auralization also necessitated extensions. This paper will first briefly mention what classic GA means, and then how it relates to computer modelling in its most common form as used by acoustic consultants. The wave-related extensions used by *TUCT* (the prediction and auralization module of *CATT-Acoustic* v9) are indicated and discussed, as is the little understood *magic step* how to go from mainly energy input data and energy reflections to a pressure impulse response (IR) to enable auralization.

The aim of this whitepaper is not to discuss details of various applied GA methods or extensions but to focus on fundamental principles and give a background for software users to critically evaluate and understand the particular methods used by the software they use or test and when reading about them in articles, papers, various thesis and PR documents. A good general GA background can be found in [1] and [2]. For an overview of the many GA-based algorithms [3] is a good start, unfortunately the article does not much discuss the limitations.

This whitepaper will use reasoning based on fundamental wave-behaviour and basic signal-processing that can be considered in everyday consulting work for a better understanding of GA and GA-based software. The aim is to help users to, along with experience and measurement feedback, acquire the necessary *gut feeling* for acoustics and wave behaviour to avoid risky unquestioning use of GA-based software and over-interpretation of the results. Ironically it can be more important with a good understanding of waves when using a GA-based software than when using FEM software that solves the wave-equation. The difficulty with GA-based modelling, and in deed even room acoustics itself, is that it is complex rather than complicated. There are many parts that have to be considered, but each part on its own is not very complicated. For fun Fig.1 shows a copy from my hand drawn lecture notes from teaching room acoustics ca. 1985 and here specifically the introduction to GA.



**Fig. 1** Lecture notes ca. 1985 showing a reflector. Left: a pure specular GA reflection via the image source, same sharp coverage all frequencies. Right: a crude drawing of the actual reflection polar due to edge diffraction (in reality also diffraction to the rear) resulting in a coverage varying with frequency but that at high frequencies approaches the GA one.

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## 2. Classical GA by hand

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Since many decades, and even several centuries, GA has been used for qualitative studies of room shape and early reflections by drawing straight lines from a source point specularly reflected over plan and section drawings of e.g. a concert hall. GA was at that time a "qualitative vehicle of the mind" when designing a room. The earliest example I personally have seen was from the original drawings of the Gothenburg Concert Hall in Sweden that opened 1935, drawings used when making a model of the hall in the early 90ies. As a curiosity that model still loads in *CATT-Acoustic* v9.1 but would not pass the now much more rigorous model *Debug in Geometry View/check*, it was an early student project.

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## 3. GA via computer modelling

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In 1968 an article was published where a computer and a 3D CAD model was used to draw the lines [4] but it was essentially still only used for qualitative analysis, such as arrivals and incidence angles of direct sound and low-order specular reflections, and early echograms which is essentially what **TUCT Window | Image Source Model** (with *Paths* on) and **Window | Time Trace** (with *Specular only* on) give with the reflection order set low, but in 3D and with many other options. A short quote from [4] describes the method used:

"The calculation procedure uses a mathematical model of a hall, which is excited by a sound pulse emitted from a fixed point source. Energy is represented by rays equally distributed over the whole or over a selected part of the solid angle. The life history of each ray is calculated assuming *geometrical reflection* at all surfaces, until the ray strikes the audience area where it is assumed to be totally absorbed. The point of impingement for all emitted rays and the time delay of the impingement relative to direct sound are calculated."

Note the use of *geometrical reflection* which is another term for *specular reflection* and that also indicates the original meaning of geometrical acoustics.

It was not until the 80ies that quantitative analysis via predicted full-length 1/1-octave band energy echograms became common and the focus became more and more on predicted measures such as  $D_{50}$  and  $C_{80}$ . As time passed the qualitative use of GA-based software for room shape analysis, which they can actually excel at, became less and less common and the focus turned to predicted measures often even by-passing looking at what is most fundamental in room acoustics, i.e. the shape over time of the echogram or IR. It is worth stressing that e.g. a  $C_{80}$  that matches recommended values for a room type tells almost nothing about how that room actually *sounds*. One way to put it is that appropriate measure values is a necessary *but not sufficient* condition for good acoustics.

When full-length echograms were predicted it was discovered that it was no longer sufficient to only calculate specular reflections, it would often give a much too long  $T_{30}$  as compared to measured and other measures like  $C_{80}$  were also not well predicted. It was realized that also non-specular reflections (initially called diffuse reflections later called scattering) had to be taken into account. Initially it was mainly via what may be called classical ray-tracing with fixed-size receiver spheres and the use of frequency-dependent scattering coefficients, it was (and is) a robust method but that did not lend itself well to what came later i.e. auralization. The necessity of handling scattering has increased over time since the majority of rooms now modelled are not concert halls but rooms that do not have a geometrically mixing shape and often have a very uneven absorption distribution, while with the typical classic concert hall, having a  $T_{30} \approx T_{\text{Sabine}}$ , the scattering seldom had a dramatic effect on reverberation time prediction. See [5] for several papers related to the necessary use of scattering in GA-based software. Due the PCs of the time not being very fast several *clever* algorithms were developed but that were not always physically reasonable such as using scattering without frequency dependence. Unfortunately some of these older algorithms are still used, perhaps slightly modified, and create confusion. One major side-track was the wide-spread use of the specular-only *hybrid method* where specularly reflected rays were used to find most of the image sources, and for many years scattering seemed forgotten [6]. It should be noted that most GA-based software now use a hybrid method, in the sense that more than one method is used, but no widely used software any longer uses *the* hybrid

method. It is e.g. typical that different methods are used for early and late reflections. All widely use software now also use frequency-dependent scattering but the overall algorithms and the scattering distributions used vary substantially [7] and the frequency-dependence is not always consistent. *CATT-Acoustic* sticks with the classic Lambert distribution [2] for which there is experience from use in acoustics and GA modelling since at least 1958 [8] and that behaves in a logical and analyzable way.

The central limitation of GA is that it does not fully take into account the wave-nature of sound, to put it bluntly it does e.g. not know what a wavelength is and has to be *tricked*, by using appropriate frequency-dependent scattering coefficients, to take into account that wavelengths vary from almost 4 m at the lower limit of the 125 Hz band to only 6 cm at the upper limit of the 4000 Hz band, but as discussed in the Introduction there are wave-related extensions and exceptions. There is however a risk that due to the extensions it is assumed, especially by new users, that there are no limitations left but that is very far from true, the extensions may in many cases matter very little but in a few cases matter much more or even be crucial. For example early reflection diffraction will in most reverberant rooms have almost no effect at all while in an office with screens it can have a big effect.

### 3.1 Reflections are based on energy, sound pressure squared, and reflection phase is not included.

This was the case until auralization was developed around 1990 that made extensions necessary, auralization will be discussed in section 4.

*TUCT* extensions:

- direct sound is based on pressure in the form of short minimum phase FIRs derived from the 1/1-octave or 1/3-octave directivities (with arrays it is a bit more involved)
- 1<sup>st</sup> order reflections are based on pressure in the form of short minimum phase FIRs derived from the 1/1-octave absorption and scattering coefficients, and of course source directivity as above
- optional early diffraction based on pressure that creates FIRs, more about that in section 3.3

### 3.2 No interference between reflections

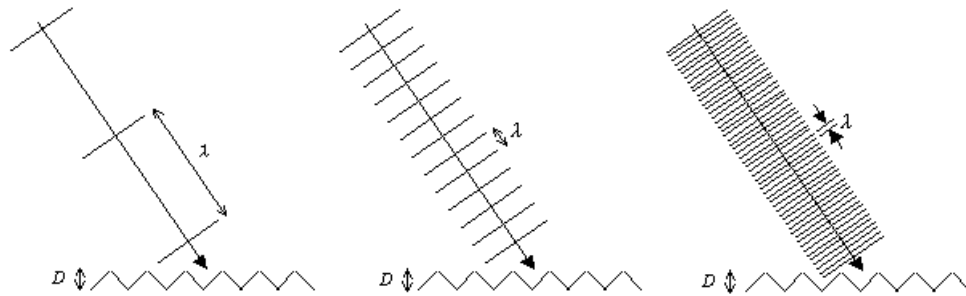
Summing two equally strong reflections as energy will always mean +3dB for all frequencies independent of differences in arrival-time, while adding the same two reflections as pressure will create interference and result in anything from +6dB to near total cancellation depending on the complex properties of each reflection, their difference in arrival-time, and frequency spectrum.

*TUCT* extensions:

- direct sound, 1<sup>st</sup> order specular and optional early diffraction interferes
- late reflections also interfere for the creation of an IR suitable for auralization. When creating an IR interference is *unavoidable*, no matter the software. This is one of the reasons for that *TUCT E* and *h* results will differ, especially in the lower bands, and that both are shown.

### 3.3 No diffraction, surface sizes must be >> the wavelength

Diffraction, which is a wave phenomenon, is not included which means that reflections can not be well predicted from surfaces that are small in relation to the wavelength. For example, a wave at 100 Hz (wavelength  $\lambda = 3.43$  m) will not reflect specularly in a  $1 \times 1$  m<sup>2</sup> surface while a 4000 Hz reflection ( $\lambda = 8.6$  cm) will give a strong specular component. A related example regarding surface detail can be seen in Fig. 2.



**Fig. 2** From [9]. Left:  $\lambda \gg D$ , the surface as a whole essentially reflects specularly (sound with long wavelengths does not "see" small surface irregularities). Center:  $\lambda \approx D$ , very complex behaviour resulting in high scattering (but in a more complex way than GA can predict in detail). Right:  $\lambda \ll D$ , each facet essentially reflects specularly so the surface as a whole will scatter (but for a different reason than for  $\lambda \approx D$ , it is rather via multiple specular redirection).

As can be realized from Fig. 2 it would be a good idea to create three separate models, one with a low Level Of Detail (LOD) for lower frequencies, one with medium LOD for middle frequencies and one with a high LOD for high frequencies. This has been tested every now and then but is not very practical and making a low-to-medium LOD model and use frequency-dependent scattering coefficients is the best compromise and as is discussed below in 3.4 it has to be accepted that low frequencies will not be well predicted with GA. The lack of full diffraction (all reflection orders) also means that only reflected sound can reach a shadow-zone of a wall reflection point, e.g. behind a screen, bookshelf and around corners. A side-effect of that is in turn that coupled rooms with a small coupling aperture can not be well predicted since diffraction takes a big part in the coupling, also for late reflections, the effective aperture area is so to speak larger than the physical area that GA "sees". Open offices are at the face of it also not good candidates for GA prediction due to many objects, bookshelves and screens that occupy a large fraction of the vertical cross-section, but at least when the ISO 3382-3 standard is used the lowest frequencies, where diffraction is the strongest, matter little due the use of both a human voice where the output level is low at low frequencies, and that a major parameter is A-weighted SPL where the effect of low frequencies is further attenuated, similarly with STI which is the other measure used by the standard.

*TUCT* extensions:

- optional early reflection diffraction, via the BTM method [10].
- frequency-dependent surface scattering coefficients (part of *CATT-Acoustic* since early 90ies) where surfaces with small details and irregularities are modelled as flat and the effect of the omitted details is compensated for by a frequency-dependent surface scattering coefficient [11]. Problematic surfaces are those that have one-dimensional scattering properties, such as corrugated surfaces and walls with battens, that reflect nearly specular along the wells/battens but with high scattering (and complex behaviour) across and here the *CATT-Acoustic* 1D Lambert can work better.
- frequency and surface-size dependent scattering (part of *CATT-Acoustic* since late 90ies) as a compensation for lack of full diffraction (i.e. for all reflection orders), called auto-edge scattering, where a small surface in relation to wavelength will create a very weak specular reflection but will instead scatter the reflection. If real diffraction is selected the auto-edge scattering is not used for the early reflections concerned but is replaced by the actual diffraction [10]. However, this can not solve the low frequency problems if a large surface has a lot of detail and these details are actually modelled. Using auto-edge scattering will then instead make the surface give a scattered reflection at low frequencies when in reality it should give an essentially specular reflection (since the long waves do not "see" the details, see more in section 6). The only way to handle this within GA is to model the big surface flat and instead have a surface scattering coefficient with low values at low frequencies and increasing with frequency.

### 3.4 Modes can not be predicted

This limitation grows more severe the lower the frequency is and the lower an 1/n-octave band is as its center frequency and bandwidth decreases. For example, the bandwidth of the 1000 Hz 1/1-octave band is 707 Hz which generally will mean that many modes will have frequencies within the band, and the details of each mode matters little, while for the 125 Hz 1/1-octave band, where the bandwidth is 88 Hz, the band may include only a few modes and their correct interference requires wave treatment. It is rather the modal density than the absolute frequency that determines the limit. In a small room modes can dominate high up in frequency so that in e.g. a control room only from 1 kHz and up may give good quantitative predictions with GA. This is quite like the classical BT (Bandwidth-Time) -product, where if a noise-like signal is measured with a fixed sample time (T) in 1/n-octave bands (B) the low frequency bars will jump up and down a lot while with increasing frequency they will become more and more stable.

*TUCT* extension:

- due to the necessity to create an IR, to be able to auralize, modes *will* be predicted but they can not be correctly predicted except in a few "clean" ideal hard-walled cases

### 3.5 Curtains and absorbers placed with an air gap against walls will not give $(2 \cdot n + 1) \cdot \lambda / 4$ absorption maxima

This is a wave effect, but the perimeter, if it is open, will with GA rather act as a trap for rays giving a very absorbing perimeter and for all frequencies. Such surfaces must therefore be modelled without an air gap, preferably as a plane sub-division, and the effect of the  $(2 \cdot n + 1) \cdot \lambda / 4$  absorption maxima must instead be included in the assigned absorption coefficient. In a similar way less absorbing surfaces modelled a small distance from a wall can also create a "ray trap" when rays are reflected many times in the narrow space. As in the example here, a good question to ask one-self as a user of GA-based software is "Can this acoustic phenomenon be solved with rays/GA as implemented by the software in question?"

### 3.6 Angle-independent absorption

Diffuse incidence absorption coefficients, as measured in a reverberation chamber, are typically used and independent of the incidence angle the absorbed fraction is the same. In reality the absorption can vary with incidence angle and in a way that is quite material dependent and requires detailed input data such as complex surface impedances and also depends on the air gap behind an absorber.

*TUCT* extension:

- From *TUCT* v2.0b a complete implementation (i.e. in all functions) of angle-dependent absorption is available but as a non-official hidden option that has to be requested. The reason is that the benefit is so far uncertain since it is really impossible to know the angle-dependence only from diffuse incidence absorption coefficients unless making several assumptions. Interested users can request the hidden option code and will then also receive a document with more discussion on the implementation and can contribute to an increasing knowledge of when the angle dependence may be an improvement so that eventually it can become an open option but with recommendations when to use it. **Note:** not available in the demo version.

### 3.7 Surface size and shape independent absorption coefficient

It has been known since the 30ies [11] and indicated in many later publications such as [1] and [12] that the absorption coefficient of especially efficient porous absorbers (say " $\alpha$ " > 0.80) depends on both the size and the shape of the absorber sample. This is the reason why many absorbers when measured give a coefficient > 1.0, even up to 1.3, but also the diffuseness of the reverberation chamber used plays a role. The classical diffuse field theory is assumed to be valid and when the geometrical area of the absorber sample (10 or 12 m<sup>2</sup>) is entered into the Sabine equation it will give  $\alpha$  > 1.0 if the *efficient* area of the absorber is larger than its geometrical area. When such an absorber is used in reality, e.g. for a

complete ceiling, it will not have the measured absorption coefficient, the question is then *which* coefficient it will have? A theory exists for modelling this wave-related phenomenon but like angle dependence it requires complex surface impedances and appears computationally very heavy [13]. If then this fact, i.e. that the actual absorption coefficient of an efficient absorber is not well known, is combined with that it is often used in the ceiling as the only dedicated absorber in many common types of rooms with a non-mixing geometry (classrooms, sports halls, open plan offices) creating a very non-diffuse field also requiring very well estimated scattering coefficients (that control the coupling between a rapidly decaying vertical sound field and a horizontal more slowly decaying field), and a good physical algorithm, it is easy to understand that the prognosis for predicting especially  $T_{30}$  in such rooms is not good. Luckily other measures like SPL, EDT,  $T_{15}$ ,  $D_{50}$ , STI are not that sensitive to the shape of the late part of the decay since the energy is low. For  $T_{30}$ , however, the line regression weights the decay section -20 to -35 dB as strongly as the section -5 to -20 dB, and the decay is often nonlinear (in dB) or has a double slope, which in itself invalidates the use of  $T_{30}$ . But lucky again is that  $T_{30}$  is typically of little consequence in rooms like that so if the age old dependence and specification of  $T_{30}$  can be discarded for such rooms the prognosis is not that bad after all.

### 3.8 Reflections from curved surfaces are less well predicted than from flat surfaces

Scattering can help when it comes to convex curved surfaces that makes the wave-front diverge but with a concave focusing surface that does not help. It also does not help if the description of a surface is analytic rather than a faceted approximation, e.g. cylindrical, quadratic, cubic or more general such as NURBS. For example, geometrical reflections from a very big<sup>1)</sup> hard flat surface can predict a close to ideal specular behaviour for all frequencies resulting in a clean Dirac-like reflection of a Dirac pulse very close to a measurement, while with a big<sup>1)</sup> hard *curved* surface the prediction will not match a measurement since e.g. for a focusing surface the focus point size is in reality frequency dependent (big for low frequencies and small for high frequencies) while with energy reflections the focus point size will have the same very small size for all frequencies.

<sup>1)</sup> big enough for edge diffraction to be negligible.

*TUCT* extension:

- with help of optional early diffraction first order reflections from curved surfaces modelled as piece-wise flat will approach the behaviour of the actual curved surface, including the frequency dependence of the focus point size of a focusing surface. Examples for convex surfaces can be seen in the comprehensive whitepaper on the diffraction implementation included with the software.

## 4. Then came auralization

Late 80ies early 90ies auralization was developed [14] and showed a lot of potential but also created difficulties since energy echograms were no longer sufficient but impulse responses  $h(t)$  were required so somehow the 1/n-octave-band ( $b$ ) energy echograms ( $E(b,t)$ ) had to be converted to pressure and reflection phase added. It is then *unavoidable* that the pressure reflections will interfere with each other so that an  $E(b,t)$  will differ from an  $h_b^2(t)$  (where  $h_b$  means  $h$  filtered to the octave-band  $b$ ), especially at low frequencies. The initial method to synthesize an IR, necessary due to less powerful PCs, was to make 1/n-octave energy echograms with a quite wide bucket size (0.05 to 1 ms) and then create the IR from these echograms (one or more pressure reflections per bucket), i.e. it was an *unholy mix* of first adding energy in each bucket and then create pressure reflections from that energy sum. This is still a common method and was also used in *CATT-Acoustic* v8 and below but in a way that did not appear to have had any big artifacts for normal use but was not as general as it became with v9 and *TUCT*. A lingering problem has been that it has not always been clear in all software that auralization has to use an IR, so while a user may have seen a predicted value of e.g. an energy-based  $C_{80}$  on the screen they have actually listened to the properties of the IR that will have a different  $C_{80}$  especially in the lower bands. This fundamental, and *unavoidable*, difference has never been hidden away in *CATT-Acoustic* but in v8 and below  $E$ - and  $h$ -based results could not be directly compared on the screen, and  $h$  was also created in a post-process, but the IR had for comparison to be exported and evaluated in a

measurement software. It was also clearly shown in my midway Ph.D. thesis in 1992 and I remember the opponent's words (he was also a GA-based software developer but is no longer active in the field): "this information should be widely communicated". To make this more clear to users is the reason why *TUCT* shows both *E*- and *h*-based echograms, decays and measures.

*TUCT* extension:

- An energy echogram is not used at all to create the IR but it is created on-the-fly by adding pressure reflections directly to the IR. This, together with the use of variants of randomized cone-tracing makes the reflection density  $n(t)$  more like in reality i.e. a natural  $n(t) \sim t^2$  or higher. In contrast, ray-tracing with a fixed-sized receiver sphere rather, after an initial increase, gives a constant  $n(t)$  which makes it harder to create natural-sounding auralization from the echograms if used as *they are* and may even introduce strong false echoes. Other methods such as variants of diffuse rain can instead give a synthetically high reflection density even with few rays but that may not give the  $n(t)$  of natural real IRs and potentially also blur the effect of actual strong isolated echoes and flutter echoes. **Note:** *TUCT* may also give false or exaggerated late echoes but that is generally due to too few rays having been used and not due to the method itself.

## 5. What is the limit ( $f_{GA}$ ) above which GA will give good prediction results?

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To some extent the well known Schröder frequency ( $f_s$ ), that depends on reverberation time and volume, can give some information but in general it gives a much too low  $f_{GA}$ . Two rooms can have the same  $f_s$  but different  $f_{GA}$  if one has many small surfaces and the other has mainly big surfaces. Further, it is not a sharp limit but rather indicates a region where it is uncertain how well GA works.

## 6. With all these limitations why is GA used at all?

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What is the alternative to GA? To use the classical diffuse field theory even for cases where it is well known that it will not work? I think we all, as acousticians, with GA have to *take the good with the bad* and realize that GA can not solve everything and be well aware of the limitations.

- A clear benefit with GA goes back to the original use as a "qualitative vehicle of the mind" i.e. it makes it possible to *think* about how a room behaves acoustically. With most wave-based methods, like FEM, the prediction results may become more accurate (*may* since FEM requires much more accurate and complex input data than GA and a detailed model) but they just give a result and say little about *why*. Since GA, in one way or another, is based on tracing rays it is often possible to figure out *why* there e.g. is a certain strong reflection and to see the effect of room shape, scattering, and absorption distribution. I would claim that *not* also using GA this way will be risky, i.e. designing only from looking at the predicted measures but not what caused them.
- GA is a clear improvement over classical diffuse field theory in that many rooms now built have very uneven absorption, a non-mixing geometry, or both. GA can, with a physically reasonable algorithm and if frequency-dependent scattering is well and consistently taken into account, predict the longer  $T_{30}$  values (often considerably longer than  $T_{Sabine}$ ) that result in these types of rooms but it is not unproblematic. Not using scattering at all in these types of rooms will give a very much too long  $T_{30}$  [9].
- GA makes it possible to look at the very multi-dimensional room acoustics "problem" from many different angles, the more viewing angles the safer and better the design can become.
- GA makes it possible to work according to a *first things first* principle : start with direct sound, especially of course if a PA system is involved, then early reflections, then a basic full calculation, then as the room design approaches the set goal use more thorough calculations. This also has the benefit that from each project something is learned and the next project will be easier and better. This is in contrast with what may be called *design by brute forces trial and error* (repeated very long calculations) where even if the end result may sometimes turn out good (enough) it may not be known *why* it did so (it happened when some rather random change was made) and very little is learned from each project so the next project will be a new black box.

- Related to above GA is an excellent way to get an independent *second opinion* but that of course assumes that there even is a *first opinion* or design idea. If a GA-based prediction is the *only opinion* and there is no experience or design idea behind the room shape or absorption placement it will be a quite risky artificial exercise.
- GA gives the possibility to auralize, in v9 with *TUCT* it requires no more than clicking a button. Auralization is not something that should be saved just for concert halls, every day use has many advantages and it is also a way to check the calculations (also the basic Prediction version can be used for that but not the Demo due to too few rays). If algorithm 1 gives a bubbly kind of sound listening to the bare IR it is likely that too few rays have been used and if using more does not help it is likely a case where algorithm 2 using deterministic ray split-up scattering is needed, but it is *very* uneconomical to always use algorithm 2. The simple rule is that if algorithm 2 takes a very long time it is not necessary, if it is necessary it will be fast enough. It is perhaps ironic that rooms with bad acoustics (such as typically having a non-mixing geometry and uneven absorption distribution) are harder both to predict and auralize well than rooms with good acoustics. But how well does a room with bad acoustics really need to be auralized? If the acoustics is bad it needs to be improved.
- GA can get by with readily available simple input data such as 1/1- or 1/3-octave absorption coefficients or that can (and often even have to) be estimated, and as discussed in 3.7 even a database of materials will not always help for high- $\alpha$  absorbers since there is an uncertainty. Estimating surface scattering coefficients is a common initial problem but is based on the (in all acoustics) so central ratio between an object or irregularity size ( $a$ ) and the wavelength. This ratio is often expressed in books about acoustics as  $k \cdot a = 2 \cdot \pi \cdot a / \lambda$  with different behaviour if  $k \cdot a \gg 1$  and  $k \cdot a \ll 1$  and generally a very complex behaviour if  $k \cdot a \approx 1$ , see Fig. 2. However, there can be no absolute recommendations, the nature of GA is not such that very firm rules can, or even should not, be given. An experienced acoustician needs to be *in the loop*.
- GA is especially useful in the early stages of a project when the crucial room shape and absorption distribution is decided, at that stage the limitation of GA matters little and all input data is then not known in detail anyway.

## 7. Things to watch out for

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This whitepaper is not meant to be a *CATT-Acoustic* room modelling tutorial but since how the model is made will affect the results, and since it is so strongly related to GA it needs to be mentioned.

- An architect's 3D model can seldom be used as *is* but has to be simplified to work with GA and the model must also be made according to certain rules (that will vary between GA-based software) so that it is possible to calculate on it in a meaningful way, it is not sufficient that a model "looks right". At all times it must be considered that it is to be an *acoustic model* suitable for GA that is to be created, and not a visual model, or the results can be partially or even totally wrong. A side-effect of the use of CAD-programs to make the models is that it seems more and more assumed that it is then not necessary to learn how the model must be made. Since the *CATT-Acoustic's* internal GEO-scripting is not much used by recent users, not even when it would be more efficient, it is perhaps assumed that the whole manual section on modelling can be ignored, or just skimmed, but it is where the information on how a model must be constructed is found *even* when a model is made in a CAD-program. Also with CAD-program modelling there are many useful features in the GEO format that can be used after export without creating the complete model "by hand".
- Another issue with absorption is that if many materials of comparable areas are used the uncertainty in each material's absorption coefficients matters little, the uncertainties will average out, while if one or a few materials dominate the coefficients of course have to be much more accurate. Take a bare concrete room where changing the coefficient from 0.02 to 0.01 will (if air absorption is not considered) double  $T_{30}$ , while if there is just a small patch of concrete among many other materials it will not matter if the coefficient is set as 0.01 or 0.05).

- Similarly if a room geometry is mixing and the absorption is evenly distributed (say a stone church or cathedral) scattering is not as crucial for  $T_{30}$  prediction as if the room geometry is non-mixing and the absorption is unevenly distributed (and especially if the absorption is high in the direction of the lowest dimension, typically the vertical dimension as in an open office, sports hall or classroom). A trap here is if absorption is tuned to fit a measured  $T_{30}$  in a room where scattering does not have a big effect (say an untreated room) and then the same model is used in another configuration with more uneven absorption (a treated room) suddenly the scattering matters a lot. What this boils down to is that even in the untreated case the scattering coefficients should be addressed, and in that case they also affect measures such as  $C_{80}$ . It is worth stressing that a measured  $T_{30}$  can almost always be matched by varying the absorption but it is not a unique solution, i.e. many absorption distributions can result in the same  $T_{30}$ , and if the matching is not done well, also including scattering,  $T_{30}$  may be the *only* measure that is matched.
- If there are cases where it can be hard to decide how to model and how to set data, and with GA there will always be, it is useful to bring out an old but still very useful engineering technique: *test and compare different ways* and both if the difference is small and if it is big the information is useful and will help also for future projects. However, be ware that a certain conclusion is case-dependent so what was found for say a church will not apply for a classroom but only for other similar churches.
- Finally, that PCs are now much faster than when GA software were first developed and used (say 1965 to 1990), and that since software now can be written to utilize parallel processing on multi-core chips, may lead to assuming that the reason that models have to be simplified for GA-based prediction simply was because PCs of the time were slow. This is however a false assumption, the requirement for simplified models, where details are omitted and instead handled by frequency dependent scattering, is fundamental to GA. Being able to use more rays will of course make it easier to achieve stable results (the stage where using an increasing number of rays will not give a significant improvement) within reasonable calculation times and being able to handle more difficult cases such as non-mixing geometries with an uneven absorption that typically require many more rays. In short, faster PCs can only improve the results *within* what GA is capable of, they will not make the inherent limitations of GA go away.

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