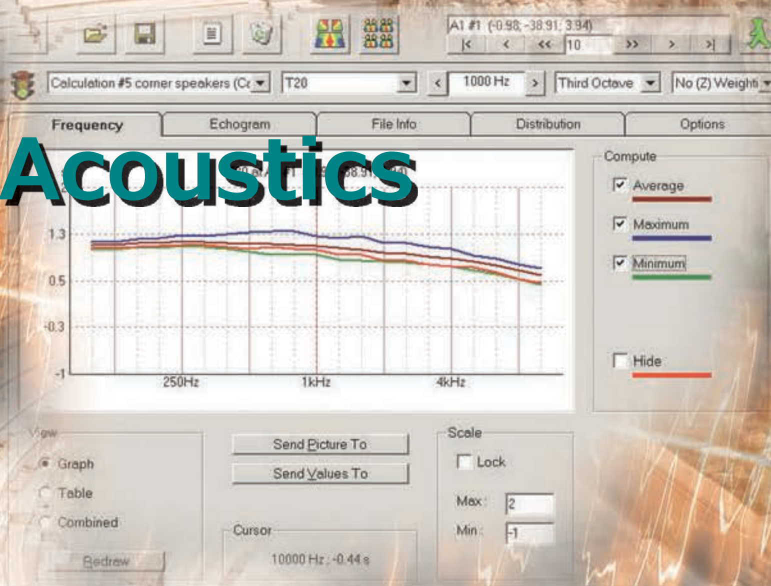
Predictive Acoustics



By
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In ancient times, the importance of acoustics in theaters was appreciated; indeed, first-century Roman architect Marcus Vitruvius Pollio discussed acoustics in Book 5 of his "Ten Books on Architecture." In 1853, Dr. J. B. Upham of Boston, MA, undertook a careful study of the acoustics of the Boston Music Hall, culminating in an essay discussing reverberation and resonance. American physicist Joseph Henry presented papers to the American Association for the Advancement of Science in 1854 and 1856, and a new lecture room in the Smithsonian Institution was built according to the results of his experiments and theory. The results were said to be highly satisfactory.

Architect T. Roger Smith published his book *Acoustics of Public Buildings* in 1861, in which he discussed the differing acoustical requirements of speech and music. John Tyndall and Lord Rayleigh (John Strutt) investigated the control of reverberation in rooms. But the definitive work that marks the birth of scientific acoustics was that of Harvard University Physics Professor Wallace Clement Sabine. In the final years of the 19th century, Sabine was tasked with remedying the acoustics of Harvard's Fogg Lecture Hall. He began with a quantitative study of the nature of reverberation and the physical factors controlling it. His equation for predicting the reverberation time of a room is still widely used:

$$RT = \frac{CV}{S\alpha}$$

where RT is the reverberation time of the room, C is a constant whose value depends upon the system of units, V is the volume of the room in cubic feet or cubic meters, S is the surface area of the room boundaries, and α is the average acoustical absorption of the boundary surfaces.

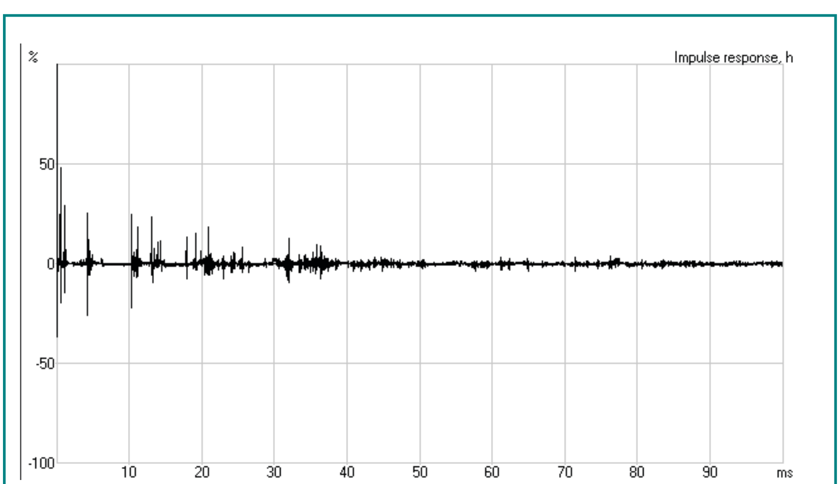


Figure 1: This impulse response shows how sound decays with time.

Reverberation Time

Sabine's equation is based on a statistical approach involving the mean free path of a sound wave between reflections and the average acoustical absorption of the room boundaries. It works well for calculating RT in rooms that meet the necessary conditions for statistical analysis: not too high an average absorption (less than 10%), a diffuse sound field, and more-or-less uniform distribution of absorption across all surfaces. Pencil-and-paper predictions using the Sabine equation were considered state of the art for many years.

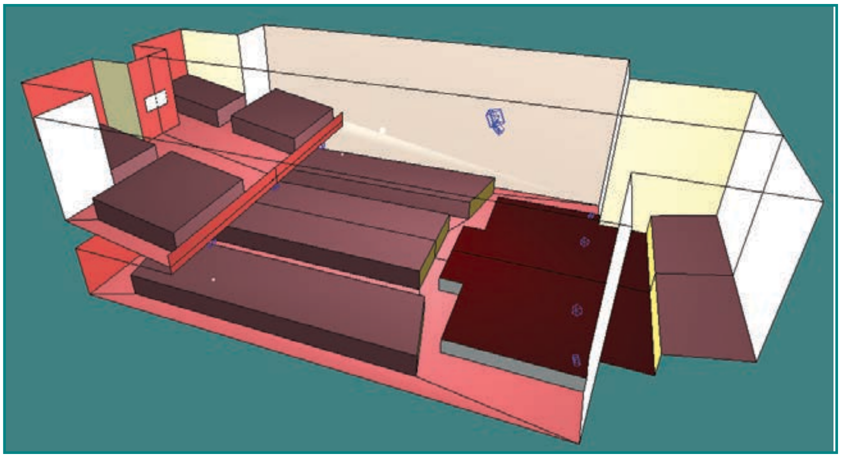


Figure 2: This rendering of a church sanctuary was created by a well-known acoustical modeling program.

With the introduction of digital computers, large institutions could greatly decrease the time it took to conduct the many calculations needed to predict RT in a real venue. PCs and affordable spreadsheet programs brought this capability to acoustical consultants and architects. However, many rooms do not meet the criteria for successful prediction using a statistical approach.

In an occupied auditorium, most of the absorption is provided by the occupants, and thus, is located on the floor, with substantially less absorption on the walls and ceiling. Deep balconies and insufficient diffusing features prevent a room from having a truly diffuse sound field.

For some very high-budget projects, scale models were built and frequency-scaled acoustic inputs were applied using miniature microphones to measure the results. However, the scale-model technique has its limitations. While wave characteristics of sound can be scaled to match the scale-model room, absorption by surfaces and air is not easily scaled. It is a tribute to acousticians of the time that so many good venues were designed in spite of design tool limitations.

Impulse Response

In 1968, Asbjørn Krokstad, Svein Strøm, and Svein Sørsdal published a paper entitled, "Calculating Room Acoustical Response by Use of a Ray Tracing Technique." This paper described a computerized method for calculating a room's impulse response (IR) using rays emitted in random directions from a source. The paths of the rays were traced mathematically using the Law of Reflection, with the strength of each reflection modified by the absorption coefficient of the surface from which the ray was reflected. From the IR, not only the RT, but many other acoustical factors could be determined.

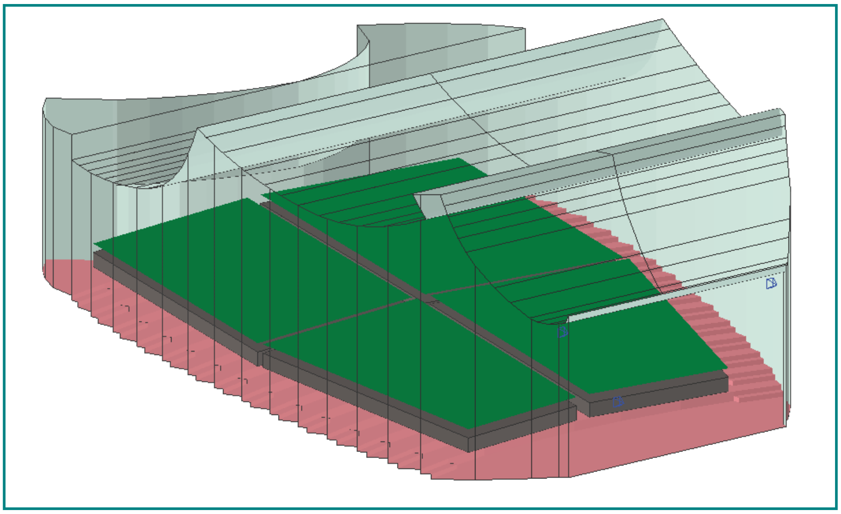
A room's IR could be described as the instantaneous sound pressure in the room, plotted as a function of time, resulting from a very brief burst of sound (the impulse). Creating a theoretically perfect IR would require an impulse whose duration is close to zero. However, an impulse that is very short compared to the RT of the room gives a satisfactory approximation. **Figure 1** shows the first 100 ms of the impulse response of a medium-sized church sanctuary.

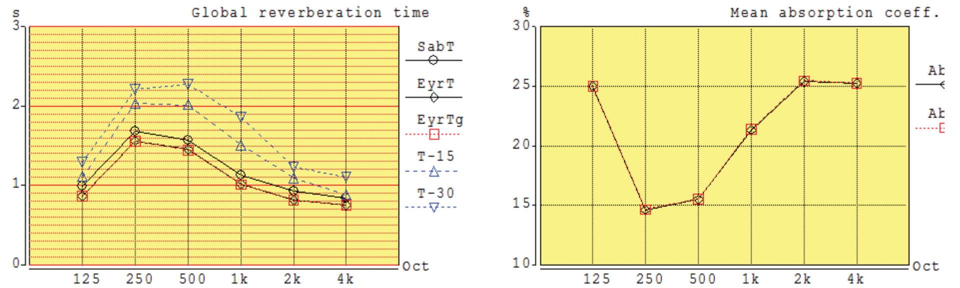
Once a room's IR is found, its RT can be predicted. Other acoustical characteristics of the room can also be predicted from the IR, including early decay time (the RT that would result if sound decayed at the same rate as it does in the first 10 ms): early-to-late energy ratios such as D50 (definition) and C80 (clarity); acoustical strength G; bass ratio (ratio of RT at low frequencies to RT at mid frequencies); treble ratio (ratio of RT at high frequencies to RT at mid frequencies); interaural correlation coefficient (IACC), which relates to perceived spaciousness; lateral energy fraction (ratio of early energy coming from a listener's sides to total energy, which also relates to spaciousness); and stage support (ratio of energy reflected from a stage enclosure to total energy). If sound in real rooms behaved according to the Sabine statistical concepts, the IR would be the same everywhere in the room. However, in actual cases, the IR varies from place to place. Using computer acoustical modeling software to predict the IR in specific places in a room enables us to see the values of RT and all these other characteristics at any desired place in the room.

Ray Tracing

In 1980, Charles Hurst of Virginia Tech presented an early paper on acoustical ray tracing to the North Carolina Regional Acoustical Society of America (ASA) chapter. This paper discussed successful predictions of a room's acoustical properties using Fortran software called RAYTR, written at Virginia Tech. Hurst and Bruce Held, a master's degree student, did most of the work. A complete prediction, including

Figure 3: Another well-known modeling program produced this rendering of an auditorium.





	125	250	500	1k	2k	4k	
EyrT	0.87	1.56	1.45	1.01	0.81	0.75	s
EyrTg	0.87	1.56	1.45	1.01	0.81	0.75	s
SabT	1.00	1.68	1.57	1.13	0.93	0.85	s
T-15	1.11	2.03	2.02	1.50	1.09	0.88	s
T-30	1.30	2.21	2.27	1.86	1.23	1.10	s
AbsC	25.01	14.63	15.48	21.33	25.42	25.24	%
AbsCg	24.99	14.64	15.54	21.41	25.47	25.28	%
MFP	6.22	6.21	6.21	6.21	6.21	6.21	m
Diffs	12.16	14.06	19.04	23.96	28.97	32.05	%

Trunc	3000.0	ms
Rays	39896	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	1.02	degrees

Figure 4: The reverberation time (RT) panel displays many different types of information.

up to third-order reflections, required several minutes to run on an IBM mainframe computer.

Since that time, personal computer speed and capacity have improved by huge margins, and a number of commercial architectural acoustical modeling programs have been released: notably, Modeler, EASE, CATT-Acoustic, Odeon, and Ulysses. All of these programs use ray-tracing algorithms to provide a plethora of acoustical predictions for the space being modeled. In addition to all the characteristics already mentioned, the algorithms can predict if and where echoes will be a problem. They also provide speech intelligibility using several different systems, and direct and total sound coverage for specific models, locations, and aiming of speakers.

Auralization

In the last two decades, the calculated IR has been put to another use: auralization. By convolving (mathematically modifying) an anechoically recorded wave file with a room's IR, one can create a very good simulation of that room's sound. Using binaural processing and good headphones, directional cues can be incorporated as well, making for a very lifelike representation of how the original sound source would sound in the specific listener location for which the IR was created. Auralization is very useful in acoustical design of listening spaces. It is also beneficial in virtual reality programs used for gaming and military training.

Modeling Programs Differ

Each acoustical modeling program has advantages and disadvantages, as well as characteristics and quirks that cause a given user to prefer one over the other. These differences include various ways of inputting the dimensions and physical characteristics of the venue, variations in the manner that the output data is presented, and special functions offered in some programs, such as walk-through auralization, which presents a visual rendering of the venue as though you were walking through it, coordinated with auralized sound corresponding to the part of the venue where the visualization shows you to be located. Although the basic ray-tracing algorithms of various programs are somewhat similar, there are details—especially those affecting auralization—that differ. **Figure 2** and **Figure 3** show examples of projects rendered by two well-known acoustical modeling programs.

Obtaining reliable results from a modeling program requires an understanding of acoustics, experience with the specific software, and an appreciation of certain basics of modeling. For example, to the uninitiated it may appear that the more detail one can include in the model, the more accurate the results. According to this line of thought, modeling stair steps shown in **Figure 3** would be better than replacing them with an inclined plane, as shown **Figure 2**.

The problem with this thinking is that sound diffracts around objects that are small compared to a wavelength and ray tracing does not capture this behavior. Thus, a sound wave's actual behavior is better simulated by the inclined plane than by stair steps that will initiate a lot of ray-scattering in the simulation, which may not actually occur in the real venue.

Figure 4 and **Figure 5** show different ways of presenting RT variation with frequency in two different modeling programs. The panel shown in **Figure 4** displays statistically calculated RT using the Sabine and the Eyring equations, with RT determined by ray tracing using the T-15 and T-30 methods, average surface absorption vs frequency, and mean free path as determined by ray tracing. The panel in **Figure 5** shows the coordinates of the location for which the RT was determined, as well as overall maximum, average, and minimum RT values. Other data is available via tabs. Statistically calculated RT values are shown in this program on a separate page. These figures are only included to illustrate some of the differences among acoustical modeling programs—differences that may affect different users in different ways.

Wave Phenomena

Sound is actually not a ray phenomenon. It is a wave phenomenon. This means that sound waves do not travel in simple straight lines, as approximated by ray-tracing algorithms. Three important wave phenomena that are not accounted for by ray tracing are refraction, diffraction, and seat dip effect.

Refraction is the bending of waves due to a change in the air's acoustical properties, as can result from temperature gradients in a large gymnasium or outdoor venue. It can cause unexpected variations in the direct sound coverage from speakers: hot spots and dead spots in the audience.

Diffraction is bending of waves around obstacles. An example is the way that sound shadows do not occur behind small pillars, at least for low and mid frequencies. A pure ray-trace would show such shadows in the coverage pattern, but you will not be able to detect the predicted dead spots by listening or by a sound-level meter. Another example is the way that sound hugs a curved sidewall rather than skimming past it or ricocheting off it.

Seat dip effect is attenuation in the audience area (occupied or unoccupied) resulting in a dip in sound pressure level between 100 and 300 Hz, beginning at the first row. It is caused by constructive and destructive interference between the direct sound and the sound reflected from the floor and seating between rows of seat backs. The severity of the dip depends on the angle between the plane containing the seat tops and the direct sound. The effect is worst at small grazing angles and is reduced as the direct-sound angle becomes steeper.

All three of these wave phenomena can be important in specific cases, and in these cases ray-tracing modeling programs may not give accurate results. The developers of these programs are aware of these ray tracing shortcomings. An improvement in these programs that has become almost ubiquitous in the last 10 to 15 years is the ability to apply scattering data.

A basic ray-tracing program assumes that when a sound wave strikes an object, all the energy is either reflected in a predictable specular way (like light), or absorbed. Depending on the surface roughness and the scale or size of the surface features compared to the wavelength of sound for which the space is being analyzed, a substantial proportion of the sound may be scattered; that is to say, specularly reflected in a way that is not practically predictable. The scattered

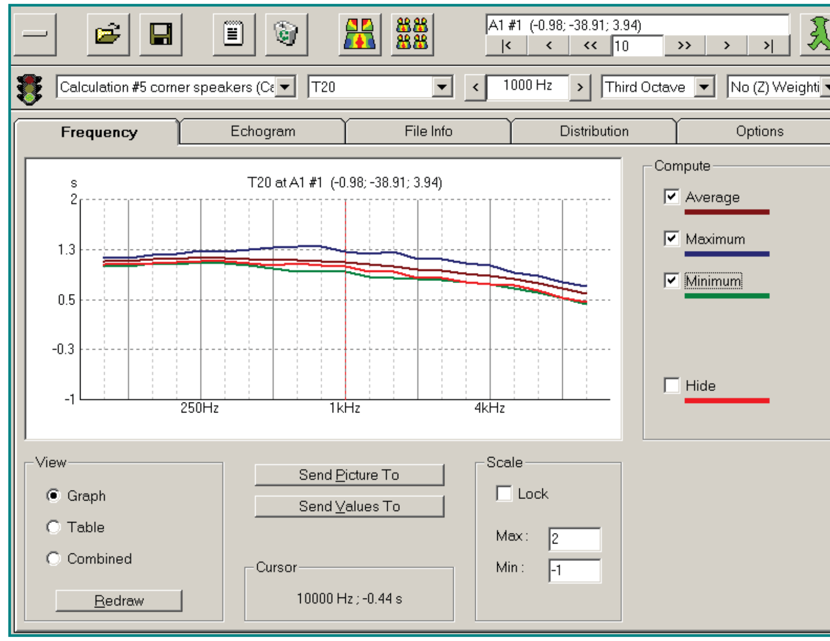


Figure 5: This RT panel shows information in a different format, which is accessible via tabs.

sound will contribute to the reverberant field but will not create echoes. Newer versions of modeling programs that apply scattering data can incorporate these features in their predictions.

Computer Modeling

An even more recent advancement in ray-tracing modeling programs is that the ability to calculate diffraction effects is now available in some of the programs. Coupled with scattering calculations, diffraction handling brings ray tracing a step closer to the exact results that would be available from a program that would rigorously solve the wave equation in the space. Still, the computational efficiency and ease of data input provided by ray-tracing programs is retained.

An acoustician who is new to computer modeling and wants to purchase modeling software can be a little overwhelmed unless (s)he has some understanding of the differences among different models. With modeling programs, the main differences are in the method of data input, the ability to incorporate scattering and diffraction, the method of presenting data output, acoustical parameters calculated by the program, the availability of manufacturers' speaker data in a form acceptable to the software, the inclusion of walk-through auralizations, and the accuracy of auralizations.

One other aspect is the expectations of the acoustician's professional partners: Is there a certain format required for models so that they can be passed back and forth among the acoustician, sound contractor, and perhaps the architect? Carefully studying the manuals of the various programs and trying out demonstration versions helps you make an informed decision.