Experimental evaluation of radiosity for room sound-field prediction

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An acoustical radiosity model was evaluated for how it performs in predicting real room sound fields. This was done by comparing radiosity predictions with experimental results for three existing rooms—a squash court, a classroom, and an office. Radiosity predictions were also compared with those by ray tracing—a “reference” prediction model—for both specular and diffuse surface reflection. Comparisons were made for detailed and discretized echograms, sound-decay curves, sound-propagation curves, and the variations with frequency of four room-acoustical parameters—EDT, RT, D50, and C50. In general, radiosity and diffuse ray tracing gave very similar predictions. Predictions by specular ray tracing were often very different. Radiosity agreed well with experiment in some cases, less well in others. Definitive conclusions regarding the accuracy with which the rooms were modeled, or the accuracy of the radiosity approach, were difficult to draw. The results suggest that radiosity predicts room sound fields with some accuracy, at least as well as diffuse ray tracing and, in general, better than specular ray tracing. The predictions of detailed echograms are less accurate, those of derived room-acoustical parameters more accurate. The results underline the need to develop experimental methods for accurately characterizing the absorptive and reflective characteristics of room surfaces, possible including phase. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2216559]

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I. INTRODUCTION

Acoustical radiosity is a geometrical sound-field prediction method that assumes diffusely reflecting boundaries. It was first developed in illumination engineering1 as radiative transfer theory, and later in the thermal-engineering community, as the theory of radiation heat transfer.2,3 Efficient methods have been developed to implement radiosity in computer graphics.4,5 For an application to acoustics, to account for the finite speed of sound, Kutturff developed the time-dependent integral equation.6,7 Acoustical radiosity has seen much development since that time.8–26 In particular, in a recent paper,19 theory and methods relating to the application of acoustical radiosity to the room sound-field prediction were presented and validated in comparison with analytical solutions. In a subsequent paper,20 the influences of various discretization parameters on the radiosity prediction accuracy were studied. Moreover, acoustical-radiosity methods were validated numerically by predicting the sound fields in cubic enclosures, and by comparing the results with ray-tracing predictions. Of primary interest here is the experimental evaluation of the accuracy of acoustical-radiosity predictions.

Various researchers have compared the characteristics of room sound fields predicted assuming diffuse, specular, or mixed specular/diffuse reflection.21–23 Radiosity has been used to elucidate the characteristics of sound fields in rooms with diffusely reflecting surfaces.21,24 Lam23 showed that different ways of implementing mixed specular/diffuse reflection (none involving radiosity) can give somewhat different prediction results. Specular ray tracing (i.e., ray tracing assuming specular surface reflection) and radiosity have been shown to give significantly different predictions, as expected for diffusely versus specularly reflecting boundaries. The difference in parameter predictions is especially pronounced in disproportionate rooms, or those with nonuniform absorption distributions. Most notably, the assumption of diffuse reflection leads to lower reverberation times, lower steady-state levels at positions not close to a source, and to lower early energy and, therefore, early-to-late energy fractions due to the temporal “smearing” of individual early specular reflections to larger times. Diffuse ray tracing makes the same physical assumptions as radiosity—energy superposition and diffuse reflection—and it has been shown that they are equivalent in their limiting cases.25 In practical cases (finite number of rays/patches in ray tracing/radiosity, and so on), predicted room parameters are very similar,19,25 but the details of the echograms may differ.20

Comparisons between radiosity predictions and measurement in rooms have been limited to sound-pressure lev-
els and reverberation times for which, in general, good agreement is found. Kang\textsuperscript{23} reports comparing radiosity predictions with scale-model results, obtaining good agreement. Shi \textit{et al.}\textsuperscript{26} report predicting reverberation times to within 1\% of the measured values in two enclosures. Of course, the reverberation time and steady-state level do not fully characterize the acoustical characteristics of a room. Objective measures that depend on the early and late parts of the impulse response are needed to more fully quantify the listener perception of a sound field. These include early-decay time, clarity, and definition.\textsuperscript{21} It is also of interest to compare the details of predicted and measured echograms and corresponding sound-decay curves.

Our primary objective in the present paper is to investigate how acoustical radiosity performs in predicting real room sound fields. This was done by comparing radiosity predictions with experimental results in three existing rectangular rooms. The rooms were chosen to have increasing nonuniformity in their geometry and surface-absorption distribution—both associated with increasingly nondiffuse sound fields—and different surface-reflection properties. Radiosity predictions were also compared with those by ray tracing, though this was a secondary objective. Ray-tracing can be considered to represent numerical experimentation,\textsuperscript{21} and has been shown to be capable of predicting room sound fields accurately.\textsuperscript{27} It was, therefore, used here as a “reference” prediction method.

\section*{II. PREDICTION APPROACHES}

The underlying concept behind acoustical radiosity is quite simple. The enclosure is divided into elements (infinitesimally small in theory, finite in size in practical applications). Each element is considered as both a receiver and a secondary source. Considered as a receiver, the energy incident on an element is just the total energy arriving from all sources (both primary and secondary) in the enclosure. When acting as a secondary source, the element is treated as a diffuse reflector; energy leaving the element is proportional to the energy incident (according to the absorption coefficient of the element)—it does not depend on the angle of incidence, and it obeys Lambert’s cosine law. In numerical implementations, form factors that give the fraction of energy leaving one element that is incident on another, are precomputed for a given environment, and stored in a look-up table. This initial “rendering” of the environment is the most computationally demanding step, after which the calculation of the sound field at any given receiver position can be done in real time.

Ray tracing involves modeling the workshop geometry and the acoustical properties (absorption and diffuse-reflection coefficients) of the surfaces, the source sound-power levels and positions, the receiver positions, and air absorption. Prediction involves tracing rays from the source as they reflect around the room, respecting the assumed reflection laws, and accounting for their energies and times of arrival when they reach the receiver position. The ray-tracing algorithm used here was the Monte-Carlo approach of Ondet and Barbry,\textsuperscript{28} developed for predicting steady-state levels in industrial workshops. It was modified to allow individual room surfaces to reflect an arbitrary proportion of incident energy diffusely (according to Lambert’s law) with the remainder reflecting specularly, as well as to predict room echograms (the pressure-squared time response at a receiver position, which results from the radiation of an energy impulse by a source). Note that this is apparently the model that Lam\textsuperscript{23} referred to as “the secondary randomized diffuse rays model.” Of course, both radiosity and ray tracing are energy-based prediction approaches that ignore the wave phase and, therefore, modal effects caused by wave interference. Thus, they would be expected to be less accurate at lower frequencies.

\section*{III. TEST ROOMS}

This investigation involved three real rooms—a squash court, a classroom, and an office—of simple, rectangular geometry, which are very different from the long rooms, industrial workshops, and concert halls involved in previous studies.\textsuperscript{22–24} Following are their descriptions.

\subsection*{A. Squash Court}

The first test room was a regulation squash court with length=9.70 m, width=6.40 m, and height=6.15 m. The walls and ceiling were of painted concrete, and the floor was of varnished hardwood. A small door allowing access into the court was located in the center of the front wall. The court had a glass window along the top 2 m of the front wall. The Squash Court was chosen for its relatively uniform geometry (length, width, and height are similar) and because all walls had similar acoustical properties. With its quasi-cubic geometry and low, uniformly distributed surface absorption, the Squash Court would be expected to contain a highly diffuse sound field, even if the hard, flat surfaces are substantially specularly reflecting.\textsuperscript{21,29}

\subsection*{B. Classroom}

As shown in Fig. 1, the second test room was an empty, medium-sized classroom with length=13.70 m, width =7.80 m, and height=2.60 m. It had walls of painted concrete, blackboards on the front and sidewalls, a short length of curtain on one sidewall, a floor of linoleum tiles on concrete, and a ceiling of acoustical tiles glued to concrete. Two doors were located on one sidewall. The Classroom was chosen because it had one dimension (the length) that is much longer than the others, and because it had a nonuniform surface-absorption distribution (the ceiling is more absorbent than the other surfaces). Thus, the contained sound field would be expected to be somewhat nondiffuse,\textsuperscript{21,29} despite the fact that some of the Classroom surfaces are sound absorbing or of panel construction, likely resulting in diffuse reflection.
C. Office

The third test room was a small, empty office, with dimensions of 5.36 m long, 3.94 m wide, and 2.71 m high. It had a floor of vinyl tile on concrete, four walls of drywall on 100 mm studs, and a suspended acoustical-tile ceiling. The Office was chosen because it was small—with relatively uniform geometry—but with a nonuniform absorption distribution (again, the ceiling is more absorbent than the other surfaces). Thus, like the Classroom, it would be expected to have a somewhat nondiffuse sound field and partially difusely reflecting surfaces.

IV. EXPERIMENTATION

In each room, measurements were made of room impulse responses between an omnidirectional loudspeaker-array source and a receiver, using the Maximum Length Sequence System Analyzer (MLSSA). The maximum-length-sequence signal from MLSSA passed through a QSC Audio USA 370 power amplifier to the speaker array in the room. A Rion NA-29E Octave-Band Analyzer converted the acoustic signal at the receiver position into an electrical signal that was transmitted back to MLSSA for analysis.

Measurements were made for source and receiver positions located along the main horizontal axis of each of the rooms. In the Squash Court the source was 1.50 m from one wall and 1.30 m high; in the Classroom it was 2.00 m from one wall and 1.30 m high; in the Office it was 0.75 m from one wall and 1.35 m high. Receiver positions were 1.3 m high, and located at 0.5, 1.0, 2.0, 3.0 m from the source, as appropriate given the room size. For the Classroom and Office, a measurement bandwidth of 12 kHz was used, allowing results in octave bands from 125 to 8000 Hz to be obtained; measured impulse responses were 1.82 s long. Because of longer reverberation times in the Squash Court, longer impulse responses were needed to obtain accurate results. Thus, the bandwidth was decreased to 6 kHz, resulting in 3.64 s long responses, providing results from 125 to 4000 Hz. Before measurements were made, the omnidirectional loudspeaker array was calibrated with respect to the radiated acoustical power for the two MLSSA bandwidths used in the tests.

MLSSA analyzed the received signal from the microphone, and calculated the cross-correlation between the received response and the original signal, to find the impulse response and the corresponding echogram. From this, steady-state sound-pressure levels, and the values of room-acoustical parameters of interest—steady-state sound-pressure level $L_p$, early-decay time EDT, reverberation time RT, definition $D_{50}$, and clarity $C_{80}$—were calculated. The (unfiltered) impulse responses were then filtered in octave bands by the MLSSA filtering algorithms, and octave-band sound-decay curves calculated. The filtered echograms and sound-decay curves were subsequently used for comparison with predicted impulse responses, echograms, and decay.

<table>
<thead>
<tr>
<th>Room</th>
<th>Surface</th>
<th>Area</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
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<tr>
<td>Squash Court</td>
<td>All</td>
<td>415.0</td>
<td>0.095</td>
<td>0.305</td>
<td>0.699</td>
<td>1.20</td>
<td>2.29</td>
<td>6.24</td>
<td>21.5</td>
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<td>Classroom</td>
<td>Room average</td>
<td></td>
<td>0.101</td>
<td>0.102</td>
<td>0.110</td>
<td>0.113</td>
<td>0.131</td>
<td>0.128</td>
<td>0.086</td>
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<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.030</td>
<td>0.040</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>Walls</td>
<td>82.2</td>
<td>0.020</td>
<td>0.010</td>
<td>0.030</td>
<td>0.030</td>
<td>0.030</td>
<td>0.040</td>
<td>0.040</td>
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<td></td>
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<td>106.2</td>
<td>0.270</td>
<td>0.280</td>
<td>0.290</td>
<td>0.300</td>
<td>0.350</td>
<td>0.340</td>
<td>0.230</td>
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<tr>
<td></td>
<td>Floor</td>
<td>106.2</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.010</td>
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<tr>
<td></td>
<td>Curtain</td>
<td>7.3</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.020</td>
<td>0.030</td>
<td>0.020</td>
</tr>
<tr>
<td>Office</td>
<td>Room average</td>
<td></td>
<td>0.081</td>
<td>0.061</td>
<td>0.055</td>
<td>0.052</td>
<td>0.080</td>
<td>0.095</td>
<td>0.087</td>
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<td>Ceiling</td>
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<td>0.140</td>
<td>0.160</td>
<td>0.170</td>
<td>0.270</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>Floor</td>
<td>21.1</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Walls</td>
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<td>0.060</td>
<td>0.050</td>
<td>0.030</td>
<td>0.020</td>
<td>0.020</td>
<td>0.030</td>
<td>0.030</td>
</tr>
</tbody>
</table>
curves. Octave-band-filtered, steady-state sound-pressure levels and other room-acoustical parameters were read directly from the MLSSA output display.

All measurements were done twice by two different experimenters, the two results being virtually identical, confirming the high quality of the experimental results.

V. PREDICTION

For each of the three test rooms, predictions were made of echograms, sound-decay curves, \( L_p \), EDT, RT, \( D_{50} \), and \( C_{80} \) using radiosity and ray tracing. To model the test rooms, their dimensions, and the same source and receiver positions as used in the experimental work, were input. The sound-power levels of the omnidirectional loudspeaker array used in the testing were used in the predictions. Results were obtained in octave bands from 125 to 8000 Hz (4000 Hz for the Squash Court), for all source and receiver positions in the rooms. Echograms and sound-decay curves are only presented for the receiver position at 3 m from the source, and for the 1000 Hz octave band. Sound-propagation curves—SP\((r)\), showing the variation with distance \( r \) of steady-state levels normalized to the source sound-power level: \( \text{SP}(r) = L_p (r) - L_w \)—are presented at 250, 1000, and 4000 Hz. Presented here are octave-band values, at the 3 m receiver position, of EDT, RT, \( D_{50} \), and \( C_{80} \), determined as follows.

(i) EDT and RT were determined, respectively, from the 0 to −10 dB and −5 to −35 dB parts of the sound-decay curves.

(ii) \( D_{50} \) and \( C_{80} \) were calculated from the echogram \( E(t) \), with time \( t=0 \) reset to the arrival time of the direct sound, as follows:

\[
D_{50} = \frac{\int_0^{50 \text{ ms}} E(t) \, dt}{\int_0^{T} E(t) \, dt} \%
\]

\[
C_{80} = 10 \log \left( \frac{\int_0^{80 \text{ ms}} E(t) \, dt}{\int_T^{T} E(t) \, dt} \right) \text{ dB},
\]

in which \( T \) is the maximum time to which the echogram was measured or predicted.

Regarding air absorption, environmental conditions in all rooms were typically 23 °C and 50% relative humidity under standard atmospheric pressure. Corresponding air-absorption exponents were found using the formulas of Bass et al., and are listed in Table I.

A difficult parameter to estimate accurately for use in prediction is the room surface-absorption coefficient, which, of course, can vary from surface to surface, and with frequency. While methods exist for measuring the acoustical properties of individual room surfaces accurately in situ, their application here was beyond the scope of the present study. Therefore, following other researchers, absorption coefficients \( \overline{\alpha} \) were estimated from measured reverberation times, by the following empirical method. First, the average octave-band surface-absorption coefficients \( \overline{\alpha} \) were found

\[
\text{TABLE II. Numerical parameters used in the radiosity predictions.}
\]

<table>
<thead>
<tr>
<th></th>
<th>Squash Court</th>
<th>Classroom</th>
<th>Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echogram length (s)</td>
<td>5.03</td>
<td>1.14</td>
<td>2.5</td>
</tr>
<tr>
<td>Echogram resolution (s)</td>
<td>1/8000</td>
<td>1/12000</td>
<td>1/12000</td>
</tr>
<tr>
<td>( t_{\text{max}} ) (s)</td>
<td>4.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( t_{\text{final}} ) (s)</td>
<td>5.0</td>
<td>1.1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

FIG. 2. Measured and predicted echograms in the Squash Court at \( r=3 \) m and 1000 Hz. Note that the amplitudes of the direct-sound and some first-reflection peaks exceed the plotted range of the abscissa.
FIG. 3. Measured and predicted echograms in the Classroom at \( r = 3 \text{ m} \) and 1000 Hz. Note that the amplitudes of the direct-sound and some first-reflection peaks exceed the plotted range of the abscissa.

FIG. 4. Measured and predicted echograms in the Office at \( r = 3 \text{ m} \) and 1000 Hz. Note that the amplitudes of the direct-sound and some first-reflection peaks exceed the range of the abscissa.
from the room-average, octave-band, measured reverberation times RT using diffuse-field theory:

\[
\bar{\alpha} = 1 - \exp \left( \frac{V}{S} \left(4m - \frac{24 \ln 10}{c\text{ RT}}\right) \right),
\]

where \(V\) is the room volume in m\(^3\), \(S\) is the surface area of the room in m\(^2\), \(m\) is the air-absorption exponent in m\(^{-1}\), and \(c\) is the sound speed in m/s. Second, absorption was distributed over the room surfaces based on physical considerations, and in such a way that the assigned absorption coefficients combined to give the average absorption coefficients found in the first step. The absorption coefficients for the rooms found by this method are given in Table I.

In order to investigate the influence of absorption distribution on radiosity prediction, absorption coefficients of surfaces in the squash court and office were varied first by 10%, then by 50%, keeping the same average values. Small changes in the predicted echograms resulted, but predicted values of the other acoustical parameters did not change. Thus, for example, the coefficients of the glued-tile ceiling in the Classroom, which were likely too high at low frequency, do not significantly affect the results, except possibly in the case of specular ray tracing.

Ray-tracing predictions were done for the cases of fully specular and fully diffuse reflection, as described in more detail below. To ensure results were statistically meaningful, representing ensemble averages, echograms averaged from those predicted for 32 different values of the integer used to initialize the random-number generator in the ray-tracing algorithm are presented.

Ray tracing was run with \(10^6\) rays traced for 500 reflections. The receiver was a cubic cell with a side length of 0.1 m. Echograms were predicted to 0.5 s with a resolution of 1/1000 s in the Squash Court, and to 1 s with a resolution of 1/36 000 s in the other two rooms. In the radiosity predictions, the surfaces of the Squash Court were divided into 291 patches, while the classroom and office had 256 patches. These subdivisions were deemed sufficient for an accurate prediction, based on previous discretization investigations and on several exploratory predictions that showed insignificant variation from the results of predictions with finer meshing. Different time-discretization periods and time limits.
were used for different sets of predictions, as indicated in Table II, which also shows the maximum times to which echograms were predicted.

VI. RESULTS

We now compare the predictions by the three models, keeping in mind the different ways they modeled surface reflection. Recall that the main objective was to evaluate the accuracy of the radiosity approach. Secondary aims were to confirm what is known about the accuracies of different prediction approaches, and the effect of different surface-reflection assumptions. In particular, we compare prediction with experiment, to evaluate the accuracy of the prediction approaches and possibly draw conclusions about the acoustical characteristics—e.g., the surface absorption and reflection properties—of the rooms.

A. Echograms

Figure 2 shows the first 50 ms of the 1 kHz echograms at \( r = 3 \) m in the Squash Court obtained from measurement, from prediction by radiosity, as well as by ray tracing for both diffuse and specular reflection. Figures 3 and 4, respectively, show the corresponding echograms for the Classroom and the Office.

In all cases, the measured and predicted echograms look somewhat different—especially in the Squash Court. In particular, radiosity, and diffuse ray-tracing are different. The
differences between the echograms predicted by radiosity and by ray-tracing are similar to those discussed in Ref. 20. The measured, radiosity, and specular ray-tracing echograms contain distinct early-reflection peaks; these are not apparent with diffuse ray tracing, which apparently smears out individual reflections. It is interesting that this does not occur with radiosity. The echogram predicted by diffuse ray tracing apparently has the least energy in the first 100 ms, that by specular ray-tracing the most, and that by radiosity an intermediate amount. In the Squash Court, the echogram predicted by specular ray-tracing apparently agrees best, though not very well, with experiment. This suggests that the Squash Court surfaces were specularly reflecting, as might be expected given its hard, flat surfaces. In the Classroom, agreement appears closest with diffuse ray tracing (and, possibly, radiosity), consistent with the occurrence of diffuse reflection. In the Office, radiosity and, surprisingly, specular ray tracing gave the closest agreement.

B. Discretized echograms

The same data that was used to create the echograms in the previous section were used to calculate the discretized echograms for the three rooms. The time resolution used to obtain these figures was 10 ms. The first 250 ms of these echograms are shown in Fig. 5. In general, radiosity and diffuse ray tracing predicted similar results, both predicting—because of the temporal smearing that results from diffuse reflection—fairly smooth variations of amplitude with time, with radiosity predicting slightly higher amplitudes. At larger times, specular ray tracing is similar; however, at shorter times, specular ray-tracing differs, predicting significant local fluctuations of energy with time, associated with individual specular reflections. None of the prediction methods accurately predicted the measured distribution of energy with time. The measured discretized echograms show fairly smooth variations of amplitude with time in the Classroom and Office, as predicted by radiosity and diffuse ray tracing, and consistent with diffuse reflection. In the case of the Squash Court, the measured discretized echograms show significant local fluctuations of energy with time, similar to those predicted by specular ray tracing, at least at shorter times; again, this is consistent with specular reflection. In general, predicted levels are higher than those measured.

C. Sound-decay curves

Figure 6 shows the measured and predicted 1000 Hz sound-decay curves at \( r=3 \) m in the three rooms. As expected from previous research, the curves predicted by radiosity and diffuse ray tracing are very similar in all cases. Those predicted by specular ray tracing have lower rates of decay, particularly in the Classroom and Office. Radiosity and diffuse ray tracing gave good general agreement with measurement, while specular ray tracing underestimated the rate of decay. Assuming that surface absorption was accurately modeled, these results suggest that the surfaces of all three rooms—especially the Classroom and Office—were somewhat diffusely reflecting at 1000 Hz.
In the Squash Court, radiosity and diffuse ray tracing accurately predicted the complete measured sound-decay curve, while specular ray tracing underestimated the decay rate slightly. This is consistent with surface absorption being well modeled, and the occurrence of diffuse surface reflection. In the Classroom, radiosity and diffuse ray tracing only predicted the initial part of the decay curves well. This could indicate that, while the absorption of surfaces close to the source was correctly modeled, that on more distant surfaces was overestimated. In the Office, radiosity and diffuse ray tracing only predicted the final part of the decay curves well, possibly indicating that, while the absorption of surfaces far from the source was correctly modeled, that on closer surfaces was underestimated.

D. Sound-propagation curves

Figure 7 shows the measured and predicted sound-propagation curves at 1 kHz in the Squash Court at 250, 1000, and 4000 Hz. Figures 8 and 9 show the corresponding results for the Classroom and Office. In all cases, the measured and predicted levels at short distances were similar, indicating that the output powers of the experimental sound source had been accurately determined. Levels predicted by radiosity and diffuse ray tracing were very similar in all three rooms and frequencies, and at all distances. Specular ray tracing predicted similar levels in the Squash Court, confirming that the type of surface reflection has little effect on steady-state levels in rooms that already have diffuse sound fields because of their proportionate geometries and uniform absorption distributions—and in the Office at 250 Hz. However, levels were higher in the Classroom, and in the Office at 1000 and 4000 Hz.

In the Squash Court, prediction agreed well with measurement at 250 Hz, was as much as 2 dB high at 1000 Hz, and was about 1 dB low at 4000 Hz. These differences are surprisingly large given the short source/receiver distances involved. They suggest that the surface absorption used in prediction was too high at 1000 Hz and too low at 4000 Hz, and may partially be due to modal effects. In the Classroom, specular ray-tracing agreed best with the measurement at 250 Hz, with radiosity and diffuse ray tracing agreeing best at higher frequencies. These results are consistent with specular reflection and correctly predicted absorption, or with diffuse reflection and underestimated absorption, at 250 Hz. At higher frequencies, the results suggest that the room surfaces were diffusely reflecting and that the absorption assumed in prediction was correct. In the Office, levels predicted by all three methods were generally higher than those measured, particularly at 4000 Hz. At 250 and 1000 Hz, the measured curves show local level variations that are likely due to modal effects, and that are not pre-
dicted. The results suggest that surface absorption at these frequencies was underestimated; conclusions regarding surface diffusion cannot be drawn.

E. Room-acoustical parameters

Figure 10 shows the variations with frequency of EDT, RT, D₅₀, and C₈₀ at r=3 m for the Squash Court. Figures 11 and 12 show the corresponding results for the Classroom and Office. In all cases, predictions by radiosity and diffuse ray tracing were very similar.

In the Squash Court, specular ray-tracing agreed well with the other two prediction approaches, except in the case of RT, for which it predicted slightly higher values due to the slightly concave sound-decay curves [see Fig. 6(a)]. Prediction generally agreed well with experiment, except at low frequencies—at which the predicted EDT’s and D₅₀’s were high, at which predicted RT’s were low at 125 Hz and high at 250 Hz, and for C₈₀ at 4000 Hz—at which the prediction was high. The worse agreement at low frequencies is likely due to surface-panel-vibration and modal effects which are not predicted.

In the Classroom, the prediction by radiosity and diffuse ray tracing generally agreed well with experiment, with a slightly tendency for EDT to be overestimated, RT underestimated, and D₅₀ and C₈₀ underestimated. As expected from the disproportionate geometry and nonuniform absorption distribution, the prediction by specular ray tracing agreed poorly with experiment, massively overestimating EDT and RT, and underestimating D₅₀ and C₈₀. In other words, the prediction underestimated the early energy relative to the late energy. At low frequency, this may, in part, be due to the excessive absorption assumed for the relatively near ceiling surface.

In the Office, similar trends occurred. Specular ray tracing again overestimated EDT and RT and underestimated D₅₀ and C₈₀. Radiosity and diffuse ray tracing gave better agreement with experiment, especially for RT, but still overestimated EDT and underestimated D₅₀ and C₈₀.

F. Discussion

Radiosity and diffuse ray tracing generally agreed closely. This is not surprising, since these are alternative energy-based prediction approaches that assume diffuse surface reflection. The one exception was in the prediction of the detailed echograms—radiosity predicted somewhat discrete early reflections, whereas diffuse ray tracing did not. In any case, this clearly did not affect derived acoustical parameters, which are predicted to be virtually identical by the two
methods. Specular ray tracing can give very different results from radiosity and diffuse ray tracing. This is particularly evident in rooms, such as the Classroom and Office, that have inherently nondiffuse sound fields and somewhat diffusely reflecting surfaces.

The results demonstrate that it is hard to draw definitive conclusions about the accuracy of the different models, or the acoustical characteristics of rooms assumed in prediction, from comparisons of prediction with experiment—even in the case of simple, rectangular rooms. If it is known that a room is accurately modeled, conclusions can be drawn about the inherent accuracy of the prediction models. If it is known that the predictions models are accurate, conclusions can be drawn about the accuracy of the room characteristics assumed in the room model. The situation is complicated by the fact that a room model includes information about both the absorption and the diffusion of the room surfaces. These have different effects on different prediction parameters; sometimes they have similar effects on a particular parameter, so that the same prediction results—and the same agreement with experimental results—can be obtained by increasing (decreasing) one of the factors and decreasing (increasing) the other. More accurate methods are needed for characterizing the absorptive and reflective properties of room surfaces, especially in situ and possibly including phase effects. The results for different parameters have somewhat different implications regarding the apparent accuracy of the room models. In other words, different values of the prediction parameters describing the rooms may be needed to predict different room-acoustical parameters; this is dissatisfying, as noted by Lam.23 Note also that only completely specular and completely diffuse reflection (modeled by Lambert’s Law) were studied here. In reality, partially specular and partially diffuse reflection may have occurred at the test-room surfaces. The low-frequency results may also be indicative of the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models. The large differences between the measured and predicted 1000 Hz impulse responses may call into question the inherent limitations of energy-based models.

In summary, the results of this work show that radiosity can predict room sound fields with some accuracy, at least as well as one other energy-based approach (diffuse ray tracing) and, in general, better than another energy-based approach (specular ray tracing). Predictions of detailed echograms—required, for example, for accurate auralization—are less accurate, those of derived room-acoustical parameters—used to evaluate the acoustical environments in the room—are more accurate. Radiosity prediction is most accurate in rooms with surfaces that—for example, because they are sound absorbing and/or of panel constructions—reflect sound somewhat diffusely. The results of this study highlight the difficulties in comparing the prediction to measurement in rooms, and the importance of developing improved methods for accurately characterizing the absorptive and reflective properties of room surfaces.

VII. CONCLUSION

In order to evaluate the accuracy of radiosity for room sound-field prediction, radiosity predictions were compared with ray-tracing predictions and measurements made in three rooms—a Squash Court, a Classroom, and an Office. Ray-tracing predictions were also made for the cases of completely specular and completely diffuse surface reflection for comparison with a “reference” prediction model. Radiosity and diffuse ray-tracing predictions often agreed closely, but were quite different from specular ray tracing. Radiosity showed reasonable agreement with experiment in some, but not all, cases. This was particularly true in the Classroom and Office, which likely had somewhat diffusely reflecting surfaces—radiosity assumes diffuse reflection. The results suggest that an assumption of purely diffuse reflection—as made by radiosity—is less limiting than an assumption of purely specular reflection.

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