PRELIMINARY EXPERIMENTAL VALIDATION OF THE RADIOSITY TECHNIQUE FOR PREDICTING ROOM SOUND FIELDS

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ABSTRACT

The radiosity technique, involving the transfer of energy between diffusely reflecting sub-sections of its surfaces, has been used to predict all or part of a room's acoustical response. However, especially in the light of the inherent assumption of diffuse reflection, there is a need to establish the applicability of the method; this was the objective of the work reported here. A radiosity algorithm for rectangular rooms was developed. Measurements were made of impulse responses in a three rooms with different size and distributions of absorption. From these relevant room-acoustical quantities – such as steady-state levels, reverberation times, early-to-late energy fractions – were calculated in octave bands. These were compared to radiosity predictions done for each room using physically-plausible input parameter values, in order to evaluate the applicability of the method.

RADIOSITY

Radiosity is a technique to compute the exchange of radiation between two surfaces. It was developed in the 1950s in the field of thermodynamics for the study of radiant heat transfer [1], and gained popularity in computer graphics in the 1980s[2]. The use of radiosity in acoustics was suggested and developed around the same time [3,4]. Unfortunately, the addition of another factor (namely time) in radiosity for acoustics adds significant increases in computation time.

In its simplest from, the one that will be used here, radiosity assumes that all surfaces in the room are diffuse reflectors. That is, it assumes that the direction of the boundary reflections does not depend on the direction of the incident sound and that the reflections obey Lambert's cosine law: I(è) ~ cos è, where I is the intensity at angle è between the boundary normal and the reflection. Using this assumption, and accounting for wall and air absorption and the finite speed of sound, intensity is propagated through the room with each surface element considered as a secondary source. Integrating over all wall elements gives the integral form of the radiosity equation [3,5].

Unfortunately, closed form solutions to the radiosity equation exist for only a few simple rooms shapes, such as the spherical enclosure [6] and the flat room [7]. In most cases, the radiosity equation must be solved numerically. This can be done by discretizing the room's interior surface into patches. The source radiates energy to each of the patches that are subsequently treated as secondary sources. Using Lambert's law, the proportion of energy leaving one patch and incident on another can be calculated. Energy is followed from patch to patch through the room. The radiosity equation becomes [8,9]:

$$I_i(t) = E_i(t) + \rho_i \sum_{j=1}^{n} I_j(t - \tfrac{r_{ij}}{c}) F_{ij} e^{-mr_{ij}}$$

n = the number of patches
ρ_i = average reflection coefficient of patch i
$I_i(t)$ = average intensity of the energy re-radiated by patch i at time t
r_{ij} = distance between patch i and patch j
c = speed of sound
m = air absorption coefficient
F_{ji} = proportion of energy emitted from patch j incident on patch i
$E_i(t)$ = average intensity of the energy radiated by patch i at time t (due to radiation from original point source)

IMPLEMENTATION

Even in this discrete form, the solution to the radiosity equation is not simple. For this preliminary investigation, further simplifications were made: rectangular enclosures, rectangular and evenly spread patches, and uniform absorption over each wall.

The calculation of form factors, F_{ij}, is one of the most difficult aspects of radiosity. Since the calculation is the same for heat, light, and sound, the many methods that have been developed for radiation transfer [1] and computer graphics [2] may be used in acoustics. For the model presented here, we used form factor geometry and closed form formulas for the form factors in rectangular enclosures with rectangular patches [1, 10]. For rectangular patches, the Ei(t) are also quite simple to calculate [8]. To solve equation (1), the iterative radiosity algorithm presented by Zhang and Shi [9] was implemented in MATLAB. Once the average patch intensities, $I_i(t)$, of all patches for all times were found, the energy density at any point r inside the room was found, according to Lambert's law, as [8]:

$$w(r,t) = w_d(r,t) + \frac{1}{\rho c} \sum_{j=1}^{n} \rho_j I_i(t - \tfrac{R}{c}) H_j e^{-mR}$$

r = position of interior point
R_j = distance between the interior point and patch j
$w_d(r,t)$ = direct contribution of energy density
H_j = the integral over the solid angle subtended by the point receiver and rectangular patch j.
The closed form formula for this was taken from Miles [8].

From the calculated energy densities, echograms, sound pressure level curves, steady state sound pressure levels, C50's, early decay times, reverberation times were computed for three rooms and compared to measured results.

ROOMS USED IN VALIDATION

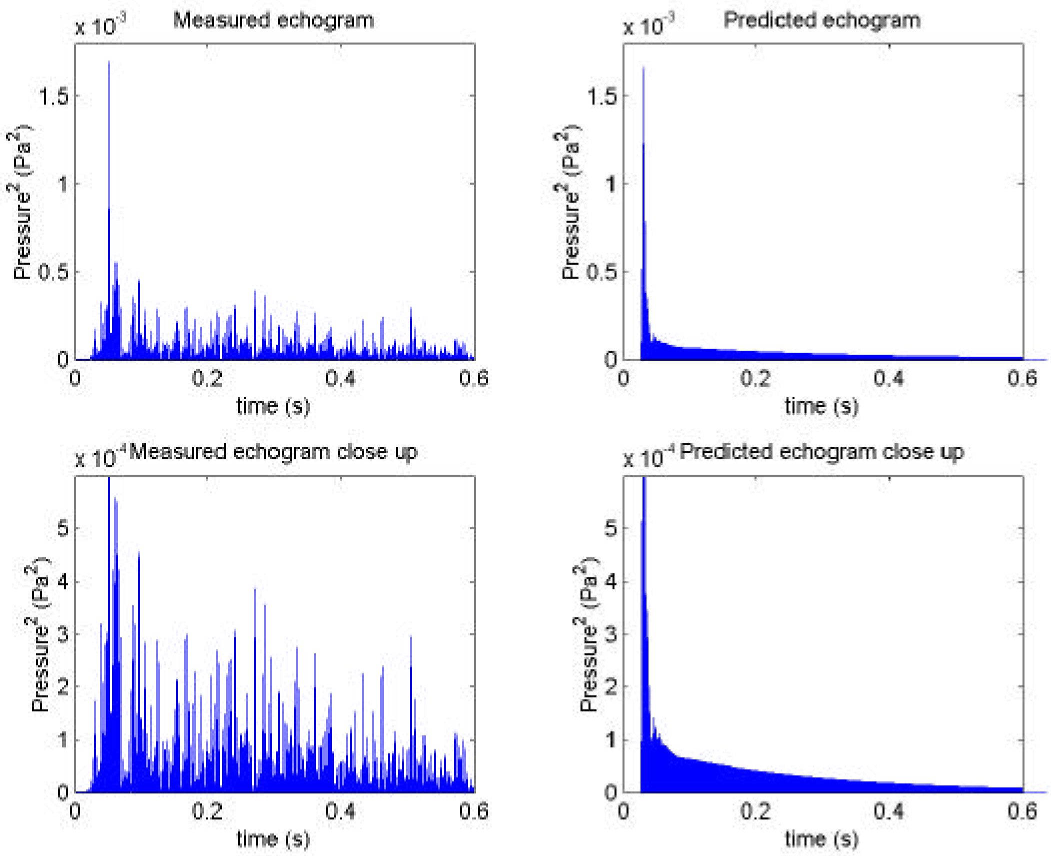
Three rectangular rooms were used to validate the radiosity technique. The rooms were chosen with increasing non-uniformity in geometry and absorption distribution. The first was a squash court with dimensions 6.4m x 9.75m x 6.65m high. The second room was a variable-acoustics chamber (room 369 of the Library Processing Center at the University of British Columbia), which we will call the environmental room, with dimensions 3.94m x 5.36m x 2.71m high. The environmental room has a floor of vinyl tile on concrete, four walls of drywall on 100mm studs, and a suspended acoustics-tile ceiling [11]. The third room was a large classroom (room 12 of the Hebb building at the University of British Columbia) with dimensions 13.7m x 7.8m x 2.6m high. Hebb 12 has walls of painted concrete, blackboards attached to three of the four walls, curtains covering a section of one wall, a floor of linoleum tiles on concrete, and its ceiling is acoustical tiles on concrete [11].

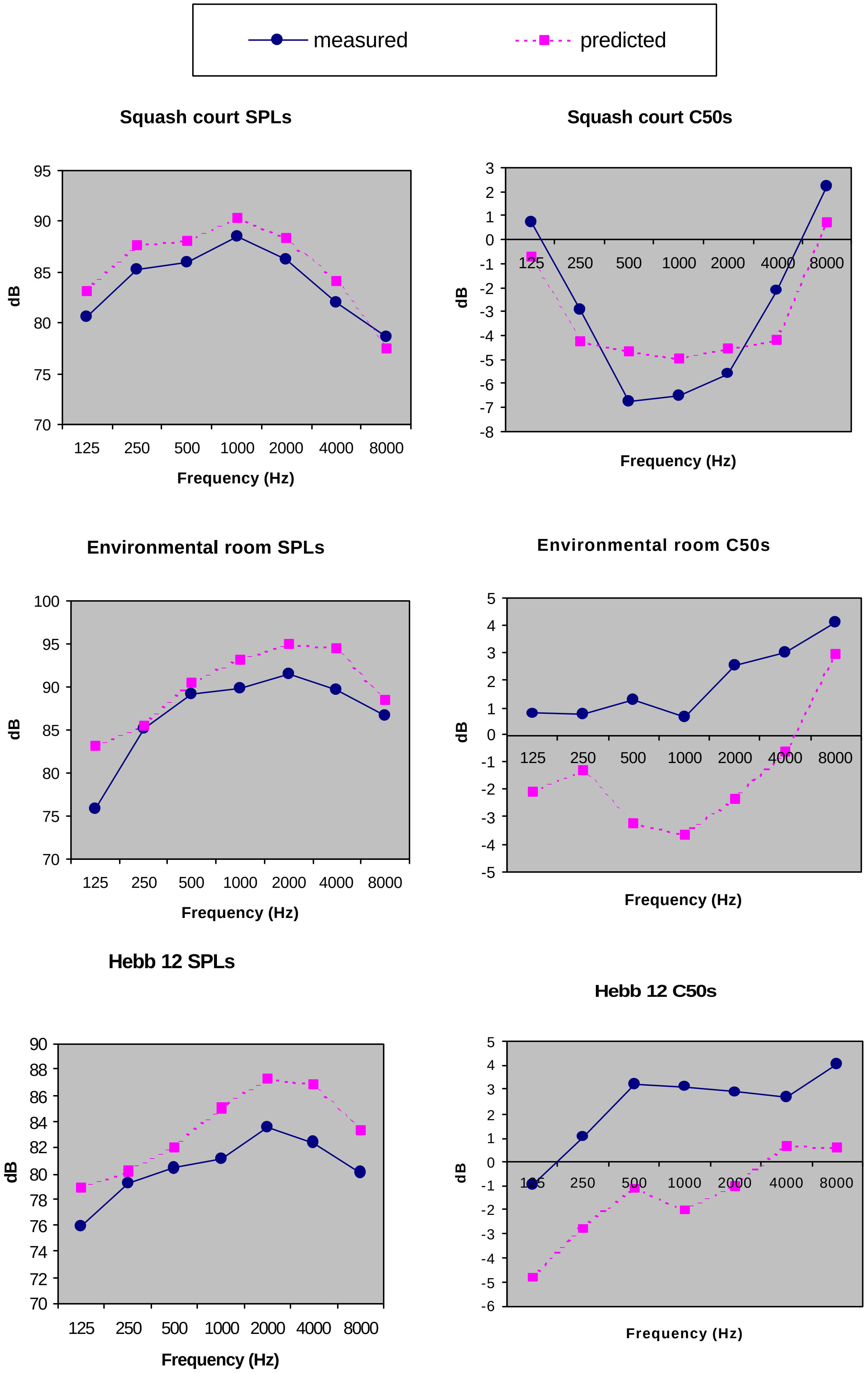
In each room, measurements were made of room impulse responses using the Maximum Length Sequence System Analyzer (MLSSA). Measurements were made for one omni-directional source position and several receiver positions (nine in the squash court, three in the other rooms). Calculations of room parameters and plots of echograms and sound decay curves were made from these measurements. The calculations were made in octave bands of 125, 250, 500, 1000, 2000, and 4000 Hz for each receiver position. Source and receiver positions and sound power levels were measured and recorded for use in the radiosity algorithm. Average absorption coefficients of the surfaces, estimated by diffuse field theory from the measured reverberation times, were found. From these, the absorption coefficients of the individual surfaces were estimated from surface areas and physical conditions for use in the radiosity algorithm.

It is important to note that the most difficult and time consuming part of radiosity – finding the form factors and then the radiosities of the patches – is based solely on the geometry of the environment and is independent of receiver position. In particular, radiosity is a view-independent process (as opposed to geometrical room acoustical models such as ray-tracing and the method of images).

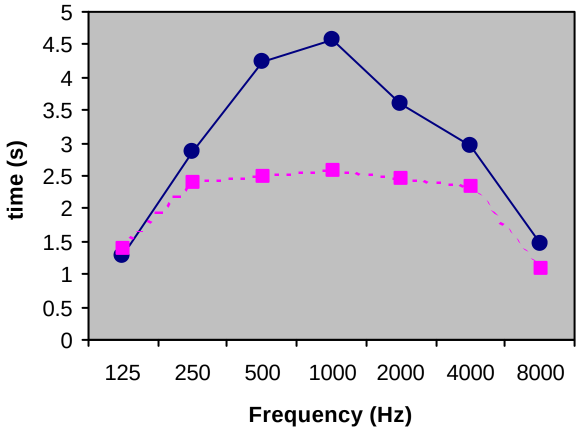
RESULTS

An example of the measured and predicted echograms (without direct sound) is given below. Also, plots of some of the measured and predicted parameters – steady state sound pressure level (SPL), clarity (C50), early decay time (EDT), and reverberation time (RT) – are given. SPL is given for one receiver position in each room and the other parameters are averaged over all receiver positions.

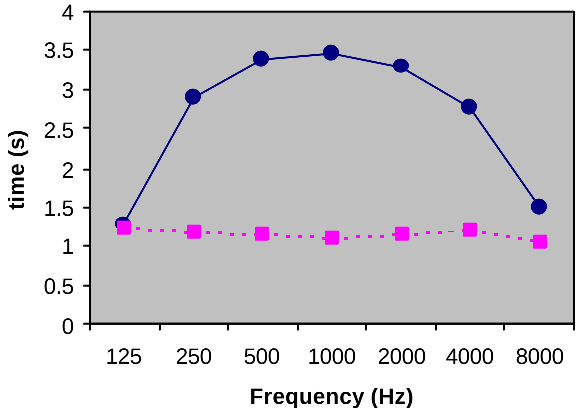



measured
predicted
Squash court SPLs
95
90
85
80
75
70
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)
Squash court C50s
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)
Environmental room SPLs
100
95
90
85
80
75
70
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)
Environmental room C50s
5
4
3
2
1
0
-1
-2
-3
-4
-5
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)
Hebb 12 SPLs
90
88
86
84
82
80
78
76
74
72
70
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)
Hebb 12 C50s
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
dB
125 250 500 1000 2000 4000 8000
Frequency (Hz)

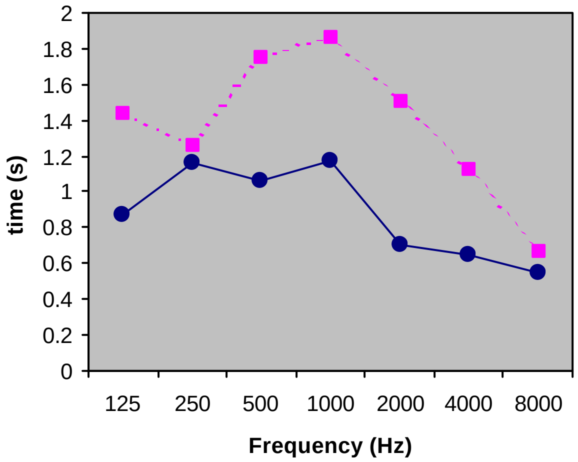
Squash court EDTs



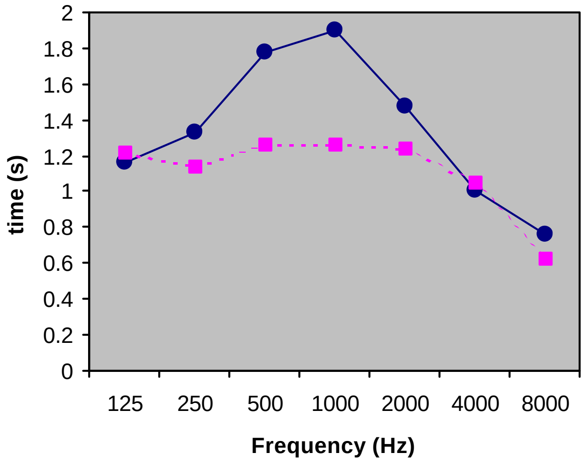
Squash court RTs



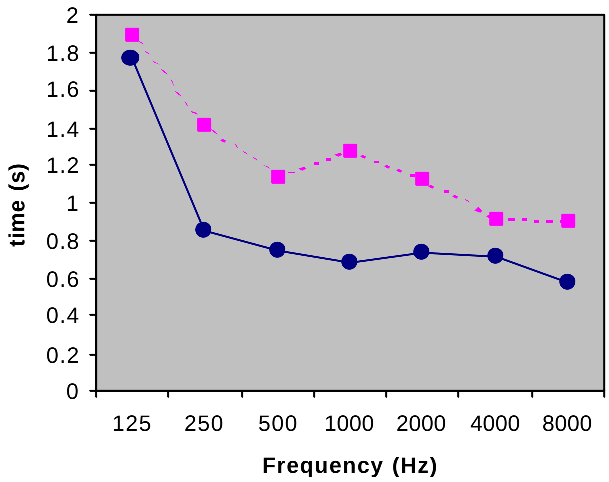
Environmental room EDTs



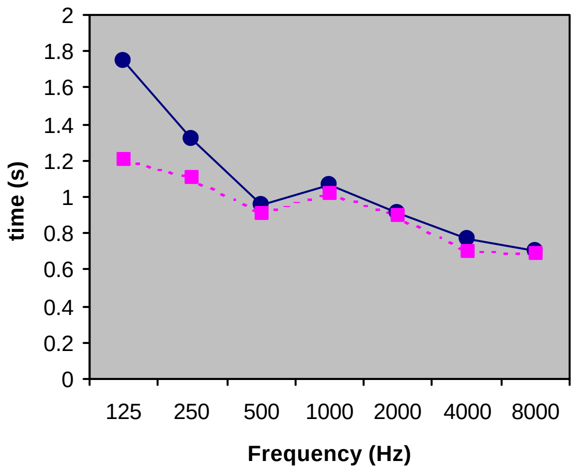
Environmental room RTs



Hebb12 EDTs



Hebb12 RTs



DISCUSSION

It is important to realize that the results presented here (and their analysis) are very preliminary. The results are rather complicated, difficult to explain, and inconclusive. Many more predictions and comparisons and further attempts at analysis are needed in addition to these preliminary results to draw firm conclusions about the applicability of radiosity to rectangular rooms. Of important consideration may be the amount and distribution of absorption used in the predictions – this was not explored. Nevertheless, some interesting and possibly revealing observations can be made.

As seen in the echograms, radiosity tends to “smear” energy in time, so that reflections arrive at the receiver position much more consistently and uniformly. This can be explained by the assumption of diffuse reflection used in radiosity. If the walls of the rooms studied here were not perfectly diffusely reflecting, this could explain differences between measurement and prediction. Smearing tends to spread some of the early energy to later energy, which may explain why predicted C50 levels tended to be lower than measured (that the amount by which some C50 predictions were lower than measured values is still of some concern). Smearing could also explain why radiosity would overestimate early decay times, although this was not a consistent result (as evidenced by the figure for EDTs in the squash court). The underestimation of reverberation times was somewhat surprising and remains to be analyzed.

In general, predictions of steady state sound pressure levels and reverberation times are quite close to measured values, although in some cases, differences of over 3dB cannot be considered close. Obviously, the results presented here suggest that radiosity overestimated sound pressure level. Once again, more measurements and predictions must be made and possible reasons should be investigated.

We could learn quite a lot about the validity of radiosity by comparing it to predictions with a ray tracing model which accounts for arbitrary specular/diffuse reflection.

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