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Characterizing the Amplitude Response of Loudspeaker Systems

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ABSTRACT
The amplitude response of a loudspeaker system is characterized by a series of spatially averaged measurements. The proposed approach recognizes that the listener hears three acoustical events in a typical domestic environment: the direct sound, the early arrivals and the reverberant sound field. A survey of 15 domestic multi-channel installations was used to determine the typical angle of the direct sound and the early arrivals. The reflected sound that arrives at the listener after encountering only one room boundary is used to approximate the early arrivals, and the total sound power is used to approximate the reverberant sound field. Two unique directivity indices are also defined and the in-room response of the loudspeaker is predicted from anechoic data.

INTRODUCTION
The basic descriptor of a linear or weakly non-linear system is the transfer function. This is best understood for simple two port electrical systems but can be applied to transducers, such as loudspeakers. However, defining the transfer function of a loudspeaker system is complicated by an additional dimension; measurement location. This complication, and the difficulty and expense associated with making truly accurate acoustic measurements, has contributed to the widespread distrust of objective measurements in the loudspeaker industry.

In 1986 Toole [1] compared the objective and subjective data for 20 loudspeakers and presented a convincing argument that the anechoic on-axis and off-axis amplitude response most closely correlates with listener preferences. He also suggested that other objective measurements such as phase response, group delay, and harmonic distortions were secondary. In [1] Toole presented several amplitude response measurements, most of which were spatially averaged. The concept of spatial averaging is not a new one and early references date as far back as 1936 [2]. There are two attributes associated with spatial averaging that make it a more attractive alternative than spectral averaging. First: spatial averaging reduces clutter associated with acoustic interference while leaving detail associated with resonance largely intact. This is because acoustic interference effects, such as diffraction, change dramatically with measurement location, while irregularities associated with resonance are spatially robust. Second: spatial averaging is more in-line with the notion that the exact location of a listener in real-world situations is not known.

In [1] Toole presented many types of amplitude response curves. These were:

1.) On-axis free-field amplitude response.
2.) Mean amplitude response in +/- 15 degree (horizontal and vertical) “listening window”.
3.) Mean amplitude response in +/- 30 to 45 degree (horizontal and vertical) annulus.
4.) Mean amplitude response in +/- 60 to 75 degree (horizontal and vertical) annulus.
5.) Mean amplitude response in the front hemisphere.
6.) Mean response in the total sphere.
7.) Total sound power.

All of these curves were derived from a series of anechoic amplitude response measurements at 2 meters. The measurements were performed over 15 degree increments in the front hemisphere and 30 degree increments in the rear hemisphere following equatorial and polar “orbits” around the loudspeaker, for a total of 34 amplitude response measurements.

While this series of amplitude responses correlated well with listener preferences in double blind listening tests, for all but the most experienced observers the curves themselves did not have clearly intuitive links back to the typical listening environment. Here we want to define a concise set of amplitude response measurements that clearly relates to the listening environment. Finally, we want to exploit today’s increased computing resources by performing individual measurements at 10-degree increments over the total sphere for a total of 70 amplitude response measurements.

MEASUREMENTS

With the exception of the in-room measurements all of the amplitude response measurement presented in this paper were made in a 10,000 cubic foot anechoic chamber fitted with 4-foot fiberglass wedges. This chamber is anechoic (+/- 0.5dB, $1/20^{th}$ octave) from 60 Hz to beyond 20kHz, and has been calibrated below 60 Hz to be accurate (+/- 0.5dB, $1/10^{th}$ octave) down to 20Hz. The measurements were made using a FFT based system, MLSSA, which is commonly used to perform gated measurements of loudspeakers in non-anechoic environments. The measurements performed in this chamber are done with a 65.5kHz sample rate and a 32768-point FFT point performed on a 500ms impulse response yielding a true frequency resolution of 2Hz.

Anechoic Versus Gated Measurements

Gated amplitude response measurements have become extremely popular within the loudspeaker engineering community and in audio equipment magazines. While these gated measurements may be more attractive than in-room measurements neither supply enough frequency resolution to reliably identify high and medium Q resonances at mid-to-low frequencies. For example: It is commonly stated that a 5ms gated measurement is accurate for frequencies above 200Hz. This is not the case. A 5ms-gated measurement has a resolution of 200Hz. This yields one-octave resolution at 200Hz, one-half an octave at 400Hz and one-tenth of an octave at 2kHz and so on. Figure 1 shows the frequency response of a loudspeaker with a high Q resonance at 250Hz and a medium Q resonance at 600Hz measured using a 500 ms impulse response (solid curve) and a 5 ms impulse response (dotted curve).

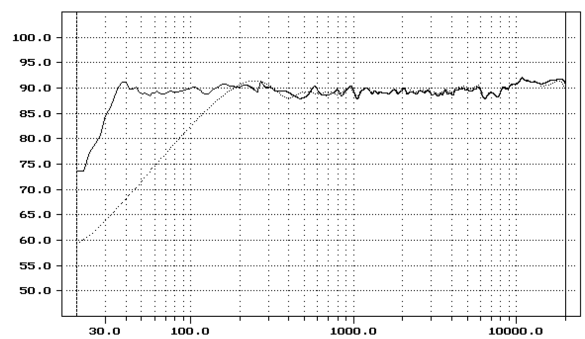

Fig. 1: On-axis amplitude response of a loudspeaker with a high Q resonance at 250Hz and a medium Q resonance at 600Hz. Solid: 500 ms gating, Dotted: 5 ms gating.

Those readers questioning the audibility of small amplitude response variations due to resonances like those in Figure 1 are encouraged to read [3].

ROOM SURVEY

In the typical domestic environment at least three distinct acoustical events occur. There is the first (or direct) sound, followed closely by several early reflections. Finally, the later arrivals form what can be loosely called a reverberant sound field. The spectrum and proportion of these sounds largely determine the timbre and spatial characteristics of the

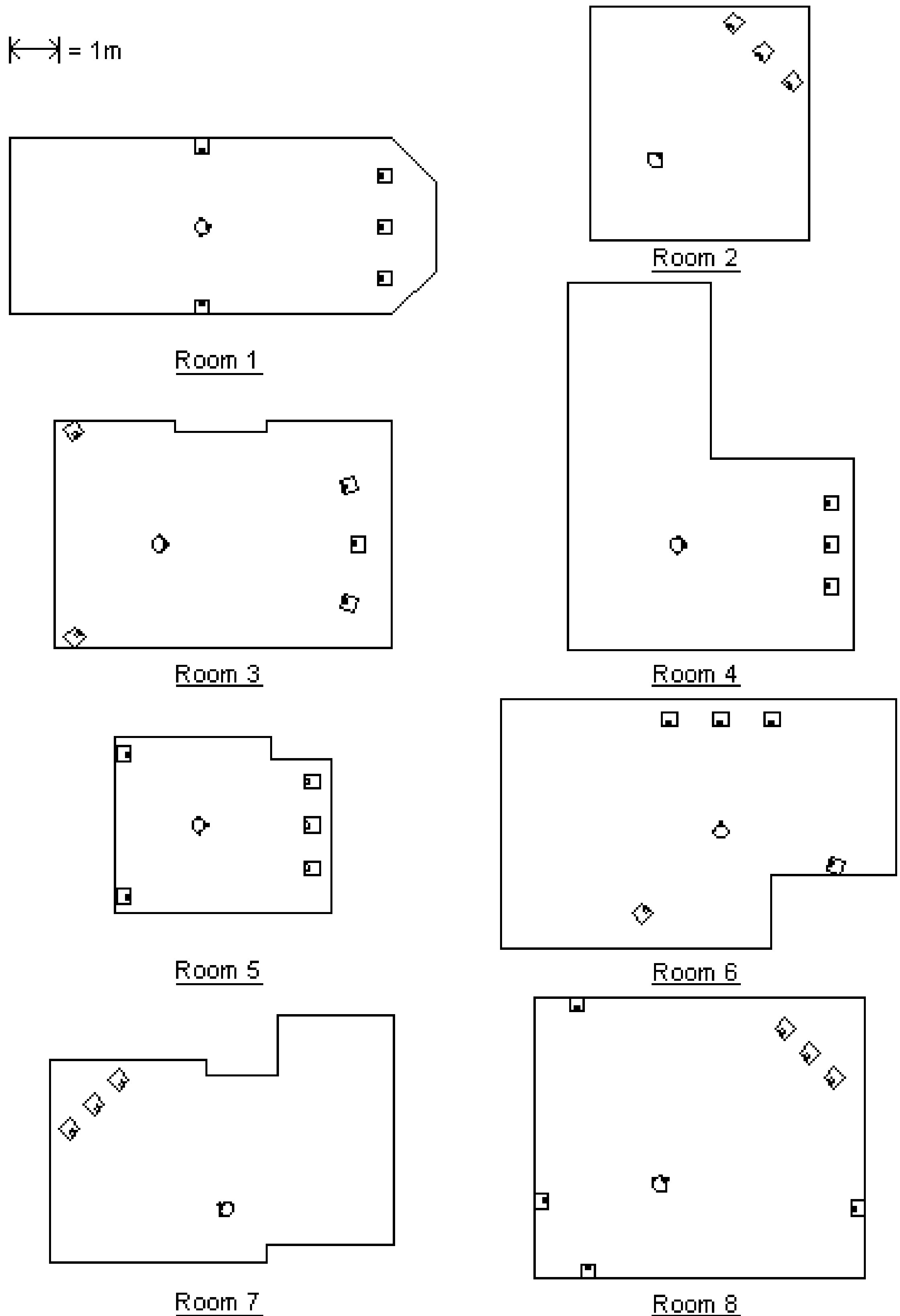

Fig. 2: Geometry of rooms 1 through 8.

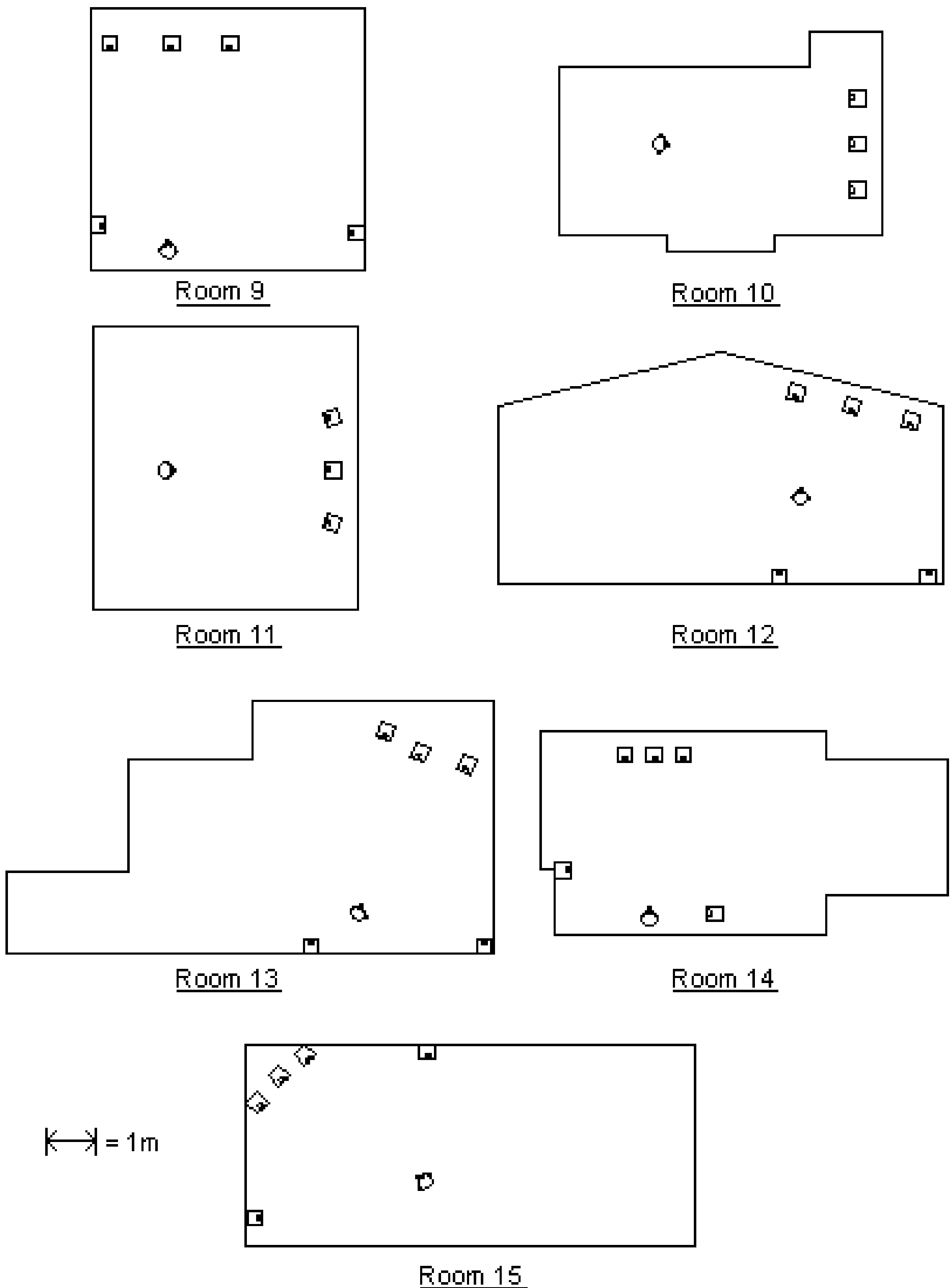

Fig. 3: Geometry of rooms 9 through 15.

loudspeaker and the listening environment. Our goal is to define three measurements that correlate with these acoustical events. The geometry of 15 typical domestic multi-channel listening environments was analyzed in an effort to define the amplitude response measurements.

Summary of the 15 Set-ups

Figures 2 and 3 show the geometry of the 15 rooms including the primary listening location and the location of the left, center, and right loudspeakers. Due to gross variations in the location of the surround speakers these were not included in the analysis. All of the rooms were located in Southern California, nine were in homes and six were in apartments.

The 15 set-ups can be divided into two groups; we will call these rectangular and triangular set-ups. Figure 4 tabulates the set-up type and the volume of each room; Figure 5 graphically depicts the distribution of the room volumes. The average room volume was 94.8 cubic meters (3348 cubic feet), nine of the set-ups were "rectangular", and six of the set-ups were "triangular". Figure 6 shows the "ray diagram" for the right speaker of room number 3 (a typical rectangular set-up). Figure 7 shows the "ray diagram" for the left speaker for room number 2 (a typical triangular set-up).

Room Number	Volume (m^3)	Home/ Apartment	Triangular/ Rectangular
1	160	Home	Rectangular
2	101	Apartment	Triangular
3	81	Home	Rectangular
4	110	Home	Rectangular
5	40	Apartment	Rectangular
6	90	Apartment	Rectangular
7	96	Apartment	Triangular
8	123	Home	Triangular
9	83	Home	Rectangular
10	56	Home	Rectangular
11	73	Home	Rectangular
12	116	Home	Triangular
13	123	Apartment	Triangular
14	72	Apartment	Rectangular
15	96	Home	Triangular
Average	95	9 Homes 6 Apartments	6 Triangular 9 Rectangular

Fig. 4: Room volumes, room type, and set-up type.

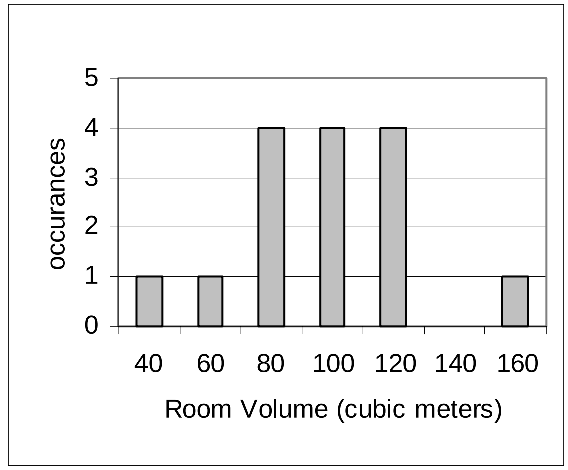

Fig. 5: Room volume distribution.

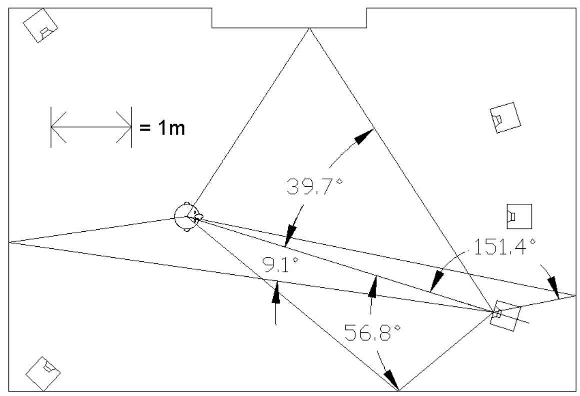

Fig. 6: Ray diagram for the right speaker of room 3 (a typical rectangular set-up).

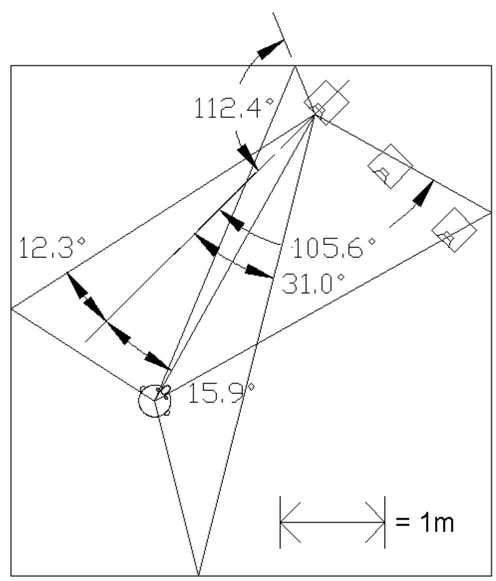

Fig. 7: Ray diagram for the left speaker of room 2 (a typical triangular set-up).

The Direct Sound

The average speaker to listener distance for the 45 front speakers was 3.3 meters (10’, 10”). All of the loudspeakers were positioned such that the listener was located within 10 degrees of the main-axis of the loudspeaker in the vertical plane. On average the listener was 10 degrees off axis horizontally, the largest angle being 26 degrees, occurring just three times. Figure 8 shows the distribution of the angles. From this data we define the “direct sound” amplitude response as a spatial average nine measurements. These measurements define a +/-10 degree vertical by +/-30 degree horizontal annulus.

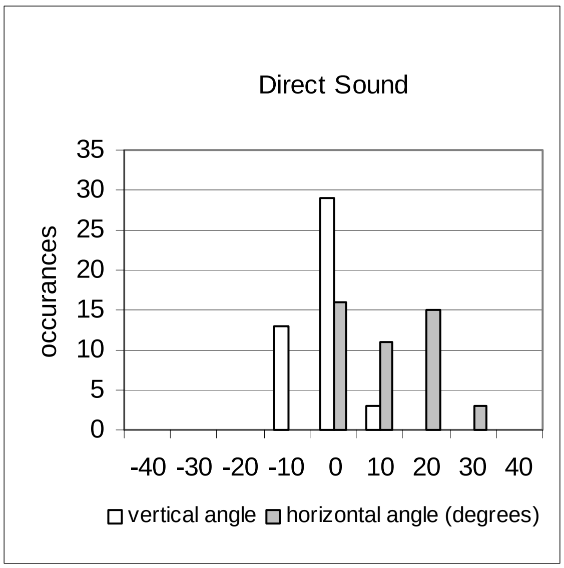

Fig. 8: Vertical and horizontal distributions for the angle of the direct sound.

The Vertical Reflections

Not surprisingly the floor reflection has the tightest distribution of all the early arrivals. On average it arrives at the listener 1.8 ms after the direct sound and occurs at an angle of 32.5 degree below the main axis. The ceiling reflection had a wider distribution due to variation in ceiling height and inclination. The average angle was 48 degrees above the main axis and arrived at the listener 4.9 ms after the direct sound. Figure 9 shows the distribution of the angles.

From this data we define the “floor reflection” as the spatial average of three measurements at 30 degrees below the main-axis +/- 10 degrees. We also define the “ceiling reflection” as the spatial average of 3 measurements at 50 degrees above the main-axis +/- 10 degrees.

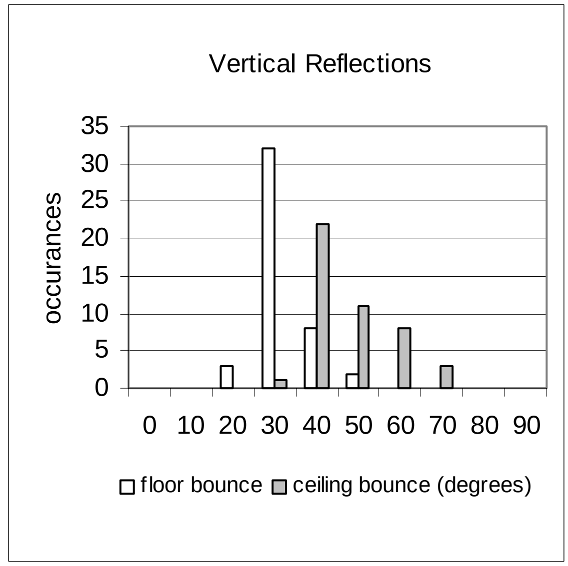

Fig. 9: Distributions for the angle of the floor and ceiling reflections.

The Horizontal Reflections

Referring to Figure 6 it would be easy to define a series of spatial averages to represent the 4 horizontal wall reflections in a rectangular set-up. One could define a “near side-wall reflection”, a “far side-wall reflection”, a “front wall reflection” and a “back wall reflection”. Indeed, the distribution of these angles is very tight. However, once the data from the triangular set-ups is included the distributions grow significantly and become bi-modal. It became clear that some sorting was required. Figure 10 shows the distribution for the horizontal reflections after they have been sorted from the smallest angle to the largest for each loudspeaker – listener location.

Clearly the horizontal reflections cannot be represented by a series of small spatial averages like the floor and ceiling reflections. Indeed, it should be clear from Figure 10 that horizontal reflections can occur at almost any angle. Therefore, in this plane we want to include all the horizontal measurements in our approximation of the early arrivals. After some experimentation and debate the following three spatial averages were defined: 1.) “Front” is the average of seven measurements at 0 degrees +/- 30 degrees. Careful readers will note this is very similar to the “direct sound”. 2.) “Side” is defined as the average of ten measurements at 60 degrees off the main-axis +/- 20 degrees to either side. 3.) “Rear” is defined as the average of 19 measurements at 180 degrees off the main-axis +/- 90 degrees (i.e.: the horizontal part of the rear hemisphere).

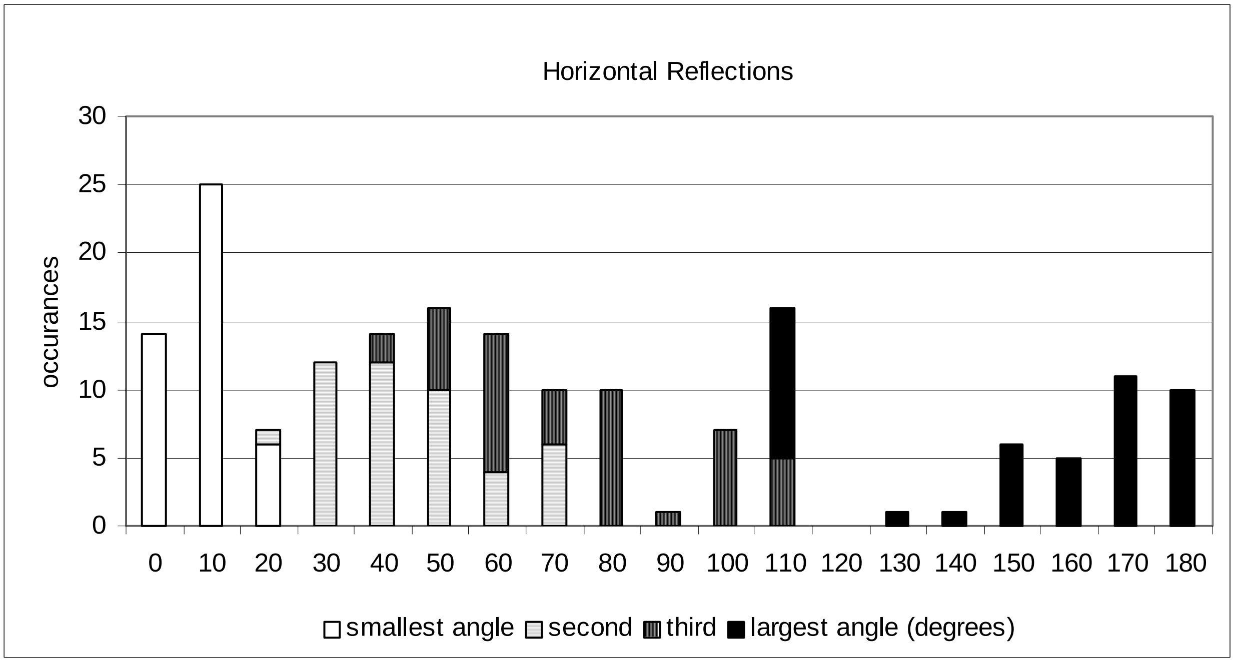

Fig. 10: Distribution of the angle for the horizontal reflections.

The First Reflections

The "First Reflections" curve is simply defined as the average of the Floor, Ceiling, Front, Side, and Rear curves. Figure 11 is the pseudo-code that neatly summarizes the computation of the curve.

```
First Reflections = Average (Floor, Ceiling, Front, Side, Back)
Where:
Floor = Average (20º down, 30º down, 40º down)
Ceiling = Average (40º up, 50º up, 60º up)
Front = Average (0º,+/-10º,+/-20º,+/-30º horizontal)
Side = Average (+/-40º,+/-50º,+/-60º,+/-70º,+/-80º horizontal)
Back = Average (180º, +/- 90º horizontal)
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Fig. 11: Pseudo-code for the calculation of the First Reflections curve.

Total Sound Power and Directivity Indices

The total sound power is used to represent the sounds that arrive at the listener ears after encountering more than one room boundary. The total sound power is the weighted average of all 70 amplitude response measurements.

The commonly accepted definition of the directivity index is the difference between the on-axis response and the total sound power. Here we have opted to replace the on-axis response with the "direct sound". Because the "direct sound" is a spatial average acoustic interference effects, such as diffraction, have been neatly removed from the directivity index.

We have defined an additional directivity index that is the difference between the direct sound and the early reflections. Typically, these directivity indices are raised by 50dB so they can be plotted on the same graph as the direct sound, first reflections and total sound power.

IMPLICATIONS ON SOUND AND SPATIAL QUALITY

In 1989 Olive and Toole published the results of some of their research on the detection of reflections [4]. Here we want to compare the early reflections that occur in a typical domestic environment to the absolute and the image-shift thresholds they defined.

In one experiment listeners were asked to identify the absolute threshold for a single simulated reflection in three different acoustic environments using speech as a test signal. The listening environments were: 1.) An anechoic chamber, 2.) The prototype for the IEC recommended listening room, and 3.) The IEC room treated to reduce early reflections, which they called the RRF room. Regardless of listening environment the absolute threshold was well below -10dB for all relevant delays. Comparing this with the data in Figure 12 clearly suggests that all of the early reflections should contribute to the perceived sound quality of the loudspeaker.

In another experiment listeners were asked to identify the point at which the position or size of the image changed as the result of a simulated reflection in the same three listening rooms. In the IEC and RRF rooms this image-shift threshold was approximately –7dB for all relevant delays. Turning to Figure 12 it should be clear that all six of the early reflections can contribute to the spatial quality of the loudspeaker.

Direct Sound		Average Delay	9.6 ms
Vertical Reflections	Floor Bounce	Average Delay	11.3 ms
		Delta	1.8 ms
		Attenuation	-1.5 dB
	Ceiling Bounce	Average Delay	14.5 ms
		Delta	4.9 ms
		Attenuation	-3.6 dB
Horizontal Reflections	Smallest Angle	Average Delay	18.9 ms
		Delta	9.3 ms
		Attenuation	-5.7 dB
	Second Angle	Average Delay	22.2 ms
		Delta	12.6 ms
		Attenuation	-6.6 dB
	Third Angle	Average Delay	18.7 ms
		Delta	9.1 ms
		Attenuation	-5.5 dB
	Largest Angle	Average Delay	14 ms
		Delta	4.4 ms
		Attenuation	-3.3 dB

Fig. 12: Average time delay and attenuation of the direct sound and the first reflections.

CORRELATION TO LISTENER PREFERNCES

Figures 13 through 16 show the amplitude response of four loudspeakers of various configurations, price and quality levels. A double blind listening test was conducted using these four loudspeakers in Harman International's Multi-Channel listening lab. In [5] Olive et al describe the lab and typical listening tests in detail. This room is fitted with a loudspeaker shuffler that allows the loudspeakers to be auditioned in the same location. The loudspeakers were placed behind a visually opaque, but acoustically transparent screen, and the levels were matched with 0.25dB using B weighting. Four listeners auditioned the loudspeakers with four pieces of music presented twice, for a total of eight evaluations. A preference scale was used to evaluate the loudspeakers. On this scale scores greater than 5 are given to loudspeakers that the listener "likes", while scores below 5 are given to loudspeakers that the listener "dislikes". Strong preferences between loudspeakers are indicated by a separation of 2 points, moderate preference by 1 point, and slight preferences are indicated by a separation of 0.5 point.

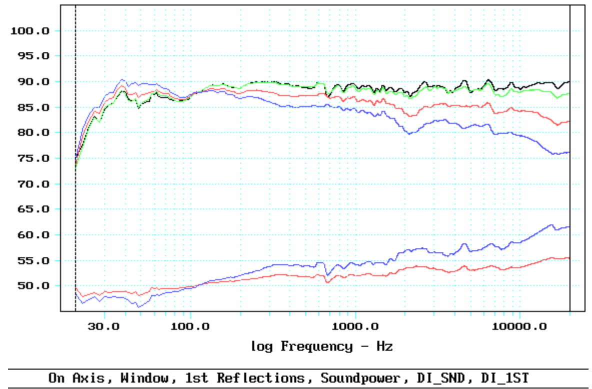

Fig. 13: Amplitude response of loudspeaker I.

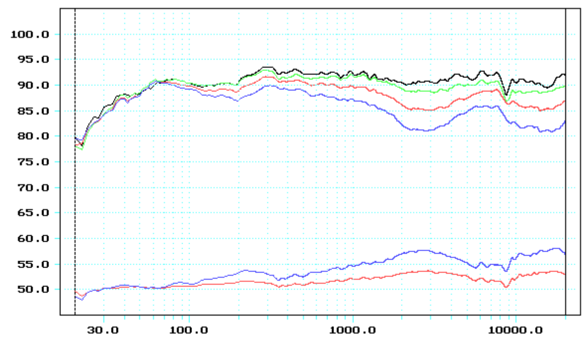

Fig. 14: Amplitude response of loudspeaker B.

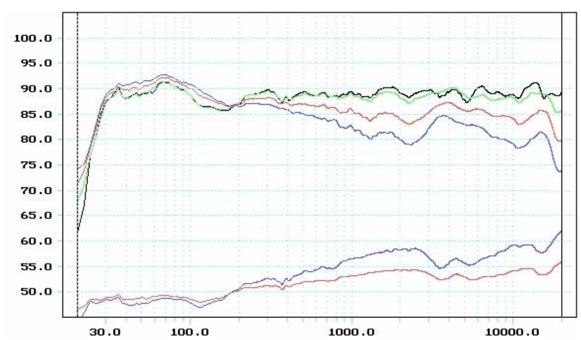

Fig: 15. Amplitude response of loudspeaker V.

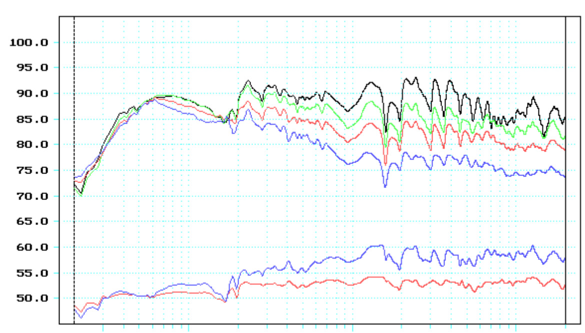

Fig: 16. Amplitude response of loudspeaker M.

Figure 17 tabulates the results of the listening test. The difference in loudspeaker preference was statistically significant for all paired comparisons except loudspeaker B and V. Loudspeaker I was slightly to moderately preferred over loudspeaker B, and strongly to moderately preferred over loudspeaker V. Loudspeakers I, B and V were all strongly preferred over loudspeaker M. From Figure 13 and 15 we see that loudspeakers I and V have similarly flat on-axis amplitude response measurements. Loudspeaker V, however, has a very non-uniform directivity index. Indeed the on-axis performance of loudspeaker V is much better than that of loudspeaker B. Clearly the non-uniform directivity of loudspeaker V is a problem. Finally, loudspeaker M makes the point that uniform directivity is a necessary but not sufficient characteristic for a loudspeaker to perform well in double blind listening tests.

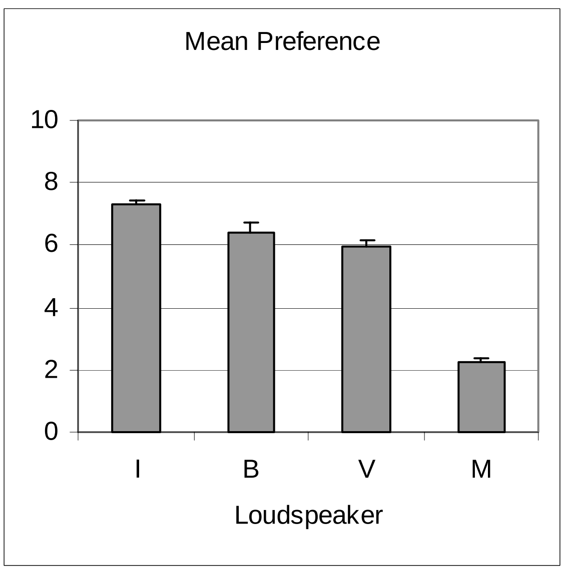

Fig: 17: Results of the double blind listening test. The solid bar represents the mean value and the error bar represents the standard error for each loudspeaker.

PREDICTED IN-ROOM RESPONSE FROM ANECHOIC DATA

In [1] Toole predicted the "in-room response" of a specific loudspeaker – room system from anechoic data. Here we have generalized the approach using our room survey for a typical listening environment.

From the data in Figure 12 we are able to estimate the contribution of the direct sound, the early arrivals and the later arrivals to a typical in-room measurement. Figure 18 shows the predicted in-room response of loudspeaker B compared to the average response measured in three different listening rooms. The correlation is excellent, especially in the critical midrange region. Errors at low frequencies are caused by room standing waves and "room gain"; errors at high frequencies are caused by absorption of reflecting surfaces and the directivity of the microphone.

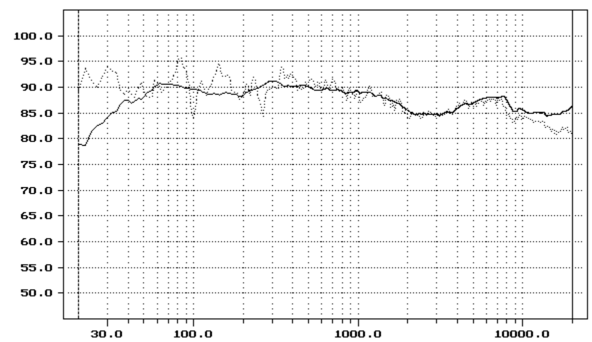

Fig. 18: In-room response of loudspeaker B. Solid: predicted from anechoic data. Dotted: average response in three rooms.

SUMMARY AND CONCLUSIONS

We have developed a concise set of amplitude response measurements that are based on the three acoustic events heard in a typical domestic environment: the direct sound, the early reflections, and the reverberant sound field. The geometry of fifteen domestic listening environments was analyzed to determine the angle and attenuation of the direct sound and the early reflections. It has been demonstrated that the early reflections are strong enough in a typical listening environment to affect the sound and spatial quality of the loudspeaker – room system. We have also shown that gated loudspeaker measurements might not have enough frequency resolution to reliably identify potentially audible resonances in the critical midrange. Finally, we are able to accurately predict the in-room response of a loudspeaker in the critical midrange region.

We have shown that these amplitude response measurements correlate with listener preferences in well-controlled double blind listening tests. For a loudspeaker to perform well in these tests the direct sound, the early reflections and the reverberant sound field must all be considered.

ACKNOWLEDGEMENTS

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The author would like to thank Joe Rogers for writing the MLSSA macros that collected the amplitude response data and calculated the various spatial averages. I would also like to thank John Slabich for drawing the room layouts and confirming the angle and attenuation of the direct sound and the early reflections.

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