ARMY RESEARCH LABORATORY

ARL Acoustic Measurements in Buildings 518 and 520 at APG

by Angélique A. Scharine, Phuong Tran, and Mary Binseel

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14. ABSTRACT

Acoustic measurements, including sound pressure levels, reverberation times, and patterns of early reflections, were made in all of the laboratory spaces used for acoustic research in the Visual and Auditory Processes Branch of the Human Factors and Engineering Directorate of the U.S. Army Research Laboratory (ARL). Reported are the data for five laboratory areas housing ten individual test chambers. These laboratory areas are situated in buildings 518 and 520 on Aberdeen Proving Ground, Maryland. Measurements were made with a Casella CEL Ltd 573.C1R sound level meter and the MLSSA (maximum length sequence system analyzer) low sound analysis software and sound card. The purpose of this report is to document the technical characteristics of the acoustic spaces used for auditory research and simulation studies at ARL

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1. Introduction

When one is conducting auditory studies, it is important to characterize completely acoustic properties of the experimental spaces used for data collection. The Visual and Auditory Processes Branch of the Human Research and Engineering Directorate, U.S. Army Research Laboratory (ARL), is in charge of five laboratory areas consisting of a total of ten test rooms in buildings 518 and 520 at Aberdeen Proving Ground (APG), Maryland. Although some spaces were documented previously, available data are not complete and in many cases, they are outdated because of the changes in acoustic characteristics of the spaces as well as in the character of the acoustic environment surrounding these spaces. Therefore, in order to determine acoustic effects of the test rooms on experimental data collected in these rooms, it was deemed necessary to conduct a new series of measurements and to make the data available to researchers who use these rooms.

The basic set of measurements conducted in all ten rooms consisted of ambient sound pressure levels and reverberation time characteristics. Three of the laboratories are large test areas that are being used in localization experiments or for the measurement of head-related transfer functions (HRTFs). In localization experiments, strong early reflections ($\Delta t < 30$ ms) of the sound from the room boundaries affect the perceived location of the sound source (Moore, 1997). The impulse response to a test signal used in HRTFs can be smeared by reflected sound if the temporal window used for data collection is not short enough to eliminate room-specific information from the recordings. In either case, it is important to know the pattern of early reflections that reaches the listener when both listener and sound source are positioned as they would be in typical experiments. Therefore, for these test areas, the patterns of early reflections have also been measured and documented.

2. Acoustic Laboratories

2.1 R-5: Headgear Evaluation and Assessment Room (HEAR)

This room was originally designed to house large computer systems and therefore has independent heating and air conditioning controls and a fan that can be switched off. It also currently contains two partially empty tanks of halon that are hidden by a sound-absorbing screen. The headgear testing assembly ("cube") is a small cube-shaped frame measuring 2.2 meters diagonally with four loudspeakers on the four vertical corner posts. The amplifier and computer that control the sound generated by the loudspeakers are housed in an adjacent room, so the room is completely empty except for the “cube” and an experimenter’s desk holding a monitor, keyboard, and mouse.

2.2 R-21: Environmental Laboratory (ELAB)

The environmental laboratory consists of a common research area (R-21) and three test rooms (R-21 A, B, and C). The common research area houses the research instrumentation stations for the three smaller chambers and a Tucker-Davis Technologies RoboArm[1] facility for measuring HRTFs. This laboratory is equipped with three Tucker-Davis System II digital signal-processing systems and supporting laboratory computers. R-21A is a medium size test room used to simulate the acoustical conditions of a living room or interior of a large cabin (V=40 m^3). Although it is being used as a control room for HRTF studies, it was measured with all equipment turned off to provide acoustic data for potential future studies. R-21B is a small (V=20 m^3), reverberant chamber that provides standardized diffuse field test conditions (American National Standards Institute [ANSI] S12.6-1997, 1997) and is appropriate for simulating vehicle interiors. Finally, R-21C is a small (V=18.7 m^3) anechoic chamber that meets free-field test conditions for frequencies above 170 Hz.

2.3 R-29: Psychophysiology Laboratory

The psychophysiology laboratory consists of a common research area (R-29), two small adjacent rooms (R-29 A and B), and two test chambers (R-29 C and D). The common research area contains research instrumentation and control systems and includes two clinical audiometers and a Tucker-Davis System II digital signal processing system. Two of the rooms, R-29A and R-29B, are permanently used for equipment maintenance and storage and were therefore not measured. R-29C is a large audiometric booth for sound field testing (V=24 m^3), and R-29D is a small audiometric booth for earphone testing (V=2.5 m^3). Various electro-acoustic and acoustic equipment and device-under-test (DUT) units are situated in R-29A and R-29B and can be used in any of the test areas.

2.4 R-30: Sound Perception Laboratory

The sound perception laboratory consists of two control rooms (R-30 and R-30 C) and two test chambers (R-30 A and B). Only the test chambers were included in the measurements. R-30A (V=30 m^3) and R-30B (V=40 m^3) are both used for speech communication studies and may also serve as small recording studios. The control rooms are equipped with two Tucker-Davis System II digital signal-processing systems and four laboratory computers dedicated to signal editing and analysis.

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[1] RoboArm™ is a trademark of Tucker-Davis Technologies.

2.5 Hostile Environment Simulator (HES)

The HES facility consists of a high energy acoustic environment capable of focusing more than 50 kilowatts of audio power at the "sweet spot" in the center of the room. The maximum sound pressure level that can be generated at the "sweet spot" can be as great as 155 dB sound pressure level (SPL). Sustained military vehicle noise, a variety of high energy impulses associated with weaponry, or other custom battle noise environments can be generated. The chamber measures 17.4 m (57 feet) long by 13.4 m (44 feet) wide by 6.7 m (22 feet) high ($V= 1576\ m^3$) and currently is used for experiments investigating sound localization, hearing protection, and impulse noise. Currently, HES has two experimental configurations, as shown in appendix A, figure A-5.

Appendix A presents diagrams of all test spaces and shows room dimensions and microphone positions for each set of measurements. In rooms where loudspeakers were used to generate early reflections, a circle with a number indicates specific locations of the loudspeakers within the room.

3. Acoustic Measurements

3.1 Background Noise Levels

3.1.1 Apparatus

A Casella CEL Ltd[2] 573.C1R sound level analyzer was used to measure the sound pressure levels in each of the laboratories. This analyzer meets the requirements for a Type I sound level meter (SLM) as stipulated in ANSI standard S1.4-1983 (ANSI, 2001) and gives slow exponential time-weighted sound levels ("A" frequency weighting) for a 10-second time sample. A "field check" calibration was performed before the measurement process in each room. A CEL-192, 0.5-inch electret free-field microphone with a frequency range of 4 to 16,000 Hz was used. A CEL-502 serial (RS232) interface and CEL-6594 (dB1) software (Casella, 2000) were used to load the data in a computer and facilitate required calculations.

3.1.2 Procedure

These measurement procedures followed the standards for the measurement of sound pressure levels in air given by ANSI S1.13 (ANSI, 1999). The ambient background noise of each of the rooms was steady and continuous. It did not vary by more than ±3 dB ("A" weighted[3]) from its mean level over the observation period. The main noise sources were from heating, ventilation,

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[2] Casella CEL Ltd™ is a trademark of Casella, Amherst, New Hampshire.

[3] "A" weighted (A-wtd) sound level measurements refer to measurements in which the sound levels of each frequency band are weighted in order to accommodate frequency-dependent changes in human auditory sensitivity at low intensity levels (see appendix B).

and air conditioning (HVAC) equipment within the building. The measurements do not reflect occasional increases in noise level caused by artillery shots at APG or by passing armored vehicles. Both broadband and one-third octave band noise levels were recorded.

The measurements usually document the noise levels measured in the center of the chamber. However, in R-5, R-21, and HES, measurements were taken in the off-center location where a listener would be seated in the experimental setup. In R-5, this was in the center of the loudspeaker array. In the main part of R-21, measurements were taken directly below the robotic arm where the listener or acoustic manikin would be placed during HRTF measurements. The HES is used with two main experimental setups. Therefore, one set of measurements was taken from the center of the bottom ring of a large, dome-shaped chandelier of 37 loudspeakers used in localization experiments. Another set of measurements was taken at an off-center location where the listener is positioned in front of three arcs of six loudspeakers each. These arcs span 30 degrees from the listener's position and are placed at distances of 4, 8, and 12 m (see the second diagram in appendix A, figure A-5).

During all measurements, the SLM was placed on a tripod in the measurement location with the microphone pointed upward. A set of two 10-s measurements was taken for each location and the average is reported here. The measurements were separated by a 1-minute interval. If the measurements differed by more than 3 dB, a third measurement was taken and the average of the two larger values was used. Measurements that were interrupted by external test firing or other irregular noises were discarded[4]. Four sets of measurements were taken in R-5; one set was taken with the lights off, and the rest with the lights on. Of the measurements with the lights out, one was taken with the HVAC blower motor off (this shuts off the fan as well), one with just the blower motor on, and one with both the blower motor and fan on. Similarly, two sets of measurements were taken in R-21 and HES to measure the contribution of lighting to the sound levels.

3.2 Reverberation Time Measurements

3.2.1 Apparatus

Reverberation times (RTs) were measured with the building acoustics software package implemented in the CEL 573.C1R sound level analyzer. This software was used to estimate the time that would be required for the sound pressure level to decrease by 60 dB (RT60) after the source ceased its action. Because it is often not possible to measure a 60-dB drop in all frequency bands, traditionally, RT60 is estimated from the time it takes for sound to decay a smaller amount. Usually, because the decay near the peak is volatile and nonlinear, the time it takes to decay the first 5 dB is not used. The time it takes for the sound level to decay from –5 dB to –25 dB is called T20; similarly, T30 is the time required for the sound level to decay

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[4] Although test fire events from the nearby testing center are common at APG, the sound level during these events is not characteristic of the general sound level. If such noises occur during experimental testing, the trial is repeated at a later time and the initial response discarded.

from –5 dB to –35 dB. We used T20 and T30 to estimate RT60 by tripling and doubling, respectively, their values (International Organization for Standardization, 1997).

The sound source used in reverberation time measurements was a .22 caliber level 2 power load detonated by a Gunnebo XL-101 low velocity stud driver (without a fastener loaded and without the firing pin in place). Figures 1 and 2 show the frequency response of the impulse noise and its waveform graph.

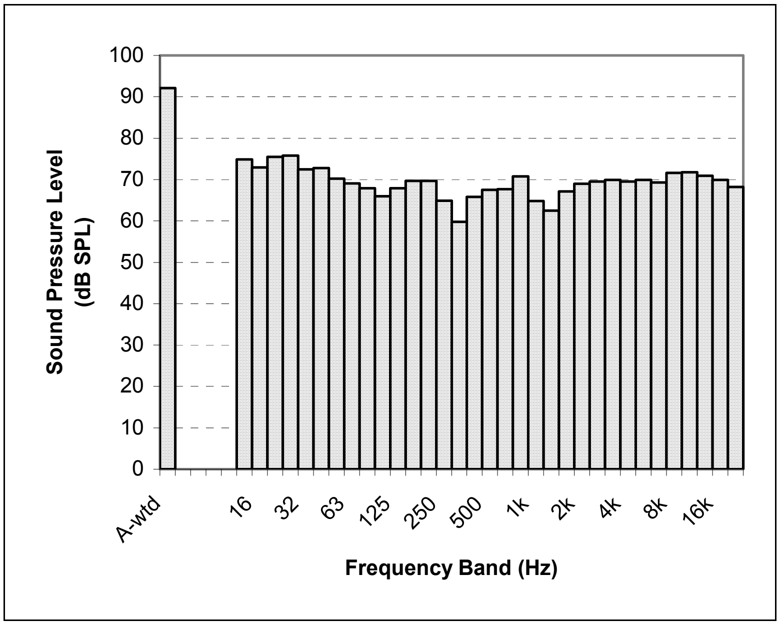

Figure 1. Frequency spectrum of the impulse noise used in reverberation time measurements.

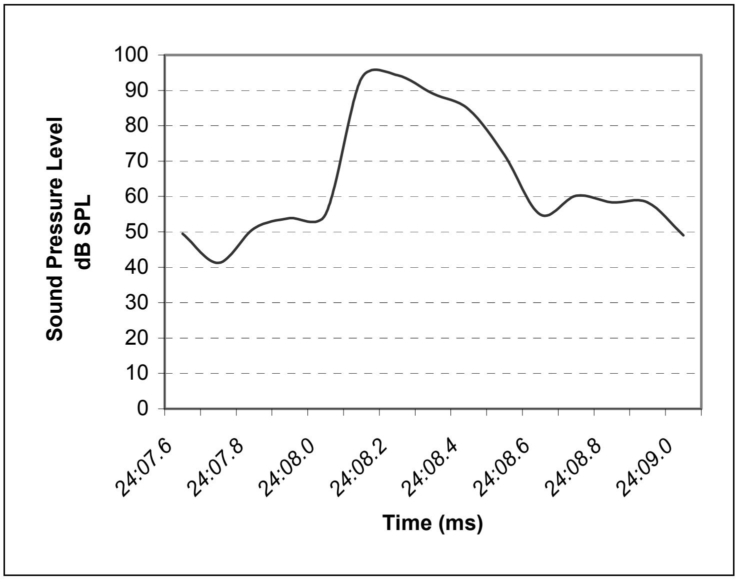

Figure 2. The amplitude of a 15-ms sample of the impulse noise used in reverberation time measurements.

3.2.2 Procedure

The CEL meter was placed in the same locations as for the sound level measurements, namely, the center of the chamber, or at the listener location if this differed from the center. In the larger chambers, multiple sound source locations were tested in order to eliminate the possibility of frequency cancellation because of interacting waveforms. No significant differences were noted and we therefore report only a single RT for each space.

The SLM was placed on a tripod in the measurement location with the microphone pointed upward. The microphone's height was 128 cm. The measurement range was set high enough to measure the residual noise levels and allow for the test sound to be at least 40 dB higher than those levels.

3.3 Room Reflections

The frequency distribution and the level of early reflections were measured in three large spaces (R-5, R-21, and HES) used for auditory localization studies. The MLSSA[5] (Rife, 1995) hardware and software was used to collect these data. The measuring system plays a maximum length sequence impulse signal and records the room response. The room response was recorded with an ACO Pacific[6] 7012 microphone with a sensitivity of 15.76 millivolts/pascal (mV/Pa) and a preamplifier gain of 40 dB.

Room reflections depend on the placement and directionality of the loudspeaker. Therefore, in these measurements, we used the loudspeakers that are normally used in these spaces. Because we chose the loudspeaker locations based on current experimental setups, the loudspeakers used in the experimental setup in R-5 do not face the walls. However, in the cases of R-21 and HES where many orientations are possible, we placed the loudspeakers in four locations so that they faced the opposite wall and incurred the earliest and largest reflections. In R-5 and R-21, the direct sound emitted was set at 70 dB SPL A-wtd. In HES, the initial level used was 65 dB SPL A-wtd. The specific descriptions of the loudspeakers and their placements in each of the rooms are described next.

3.3.1 R-5: HEAR

As presented in appendix A, figure A-1, this experimental setup has four loudspeakers placed on the vertical posts of a "cubic" metal frame. Therefore, the impulse signal was sent once through each of the four loudspeakers. The loudspeakers are all 40-watt Pioneer TS-879 87-mm coaxial loudspeakers with a frequency response of 90 to 20,000 Hz. Figure 3 shows the frequency response of one of the speakers as measured with the same MLSSA system and microphone. The frequency responses of all the TS-879 speakers were similar.

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[5] maximum length sequence system analyzer.

[6] ACO™ is a trademark of ACO Pacific, Inc.

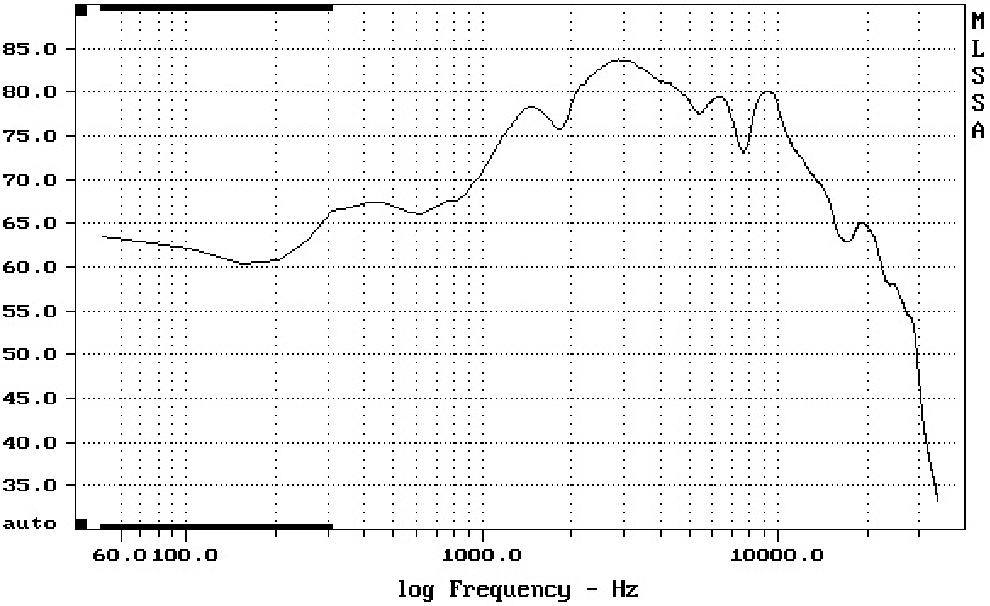

Figure 3. Characteristic frequency sensitivity of the speakers used in R-5 and HES, as measured with the MLSSA system.

3.3.2 R-21: ELAB

As presented in appendix A, figure A-2, this laboratory houses a facility for the measurement of HRTFs. The loudspeaker used in these measurements is mounted on a Tucker-Davis Technologies robotic arm and can be rotated 360 degrees. The loudspeaker is a 2-watt CUI[7] GF0876 87-mm radial loudspeaker with a frequency range of 200 to 16,000 Hz. Figure 4 shows the frequency response of this speaker, as measured with MLSSA. We took measurements of reflections from the four locations indicated on the diagram. These locations were chosen so that the loudspeaker is always directly facing an opposite wall.

3.3.3 HES

As shown in appendix A, figure A-5, this room contains a large dome-shaped array of 37 loudspeakers. The dome has three circular rings with 12 loudspeakers mounted on each ring. An additional loudspeaker is placed at the top of the dome. The loudspeakers are the same kind as those used in R-5 (Pioneer TS-879). Impulse sounds were played from the four loudspeakers directly facing the opposite walls, as indicated on the diagram.

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[7] not an acronym

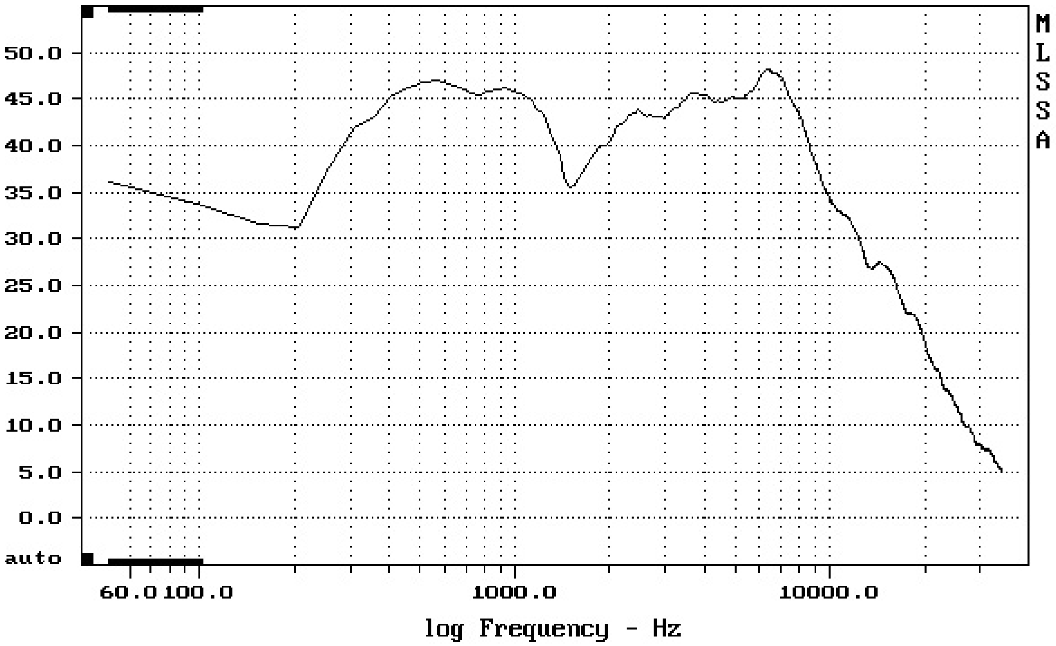

Figure 4. Frequency sensitivity of the speaker used in R-21 as measured by the MLSSA system.

4. Results

4.1 Background Noise Levels

4.1.1 R-5

The measured data are shown in table 1. There are three notable characteristics of the background noise in R-5. First, the noise levels were very much affected by whether the air conditioning (AC) blower was turned on or off (42.5 versus 28.7 dB A-wtd) and if the fan was on (44.6 dB A-wtd). Second, when the AC system and fan are operating, this is a relatively noisy space. Finally, comparison of sound levels with the lights on versus with the lights off shows that the lighting noise adds to the overall noise level, especially in the octave band centered on 630 Hz.

Table 1. R-5 – Background noise levels (L_{eq} dB).

Band (Hz)	**Lights off**	**Lights On**		
		Blower off/fan off	**Blower on/fan off**	**Blower on/fan on**
A-wtd	**26.9**	**28.7**	**42.5**	**44.6**
Linear	54.1	54.5	53.2	70.6
20	46.1	45.9	50.0	60.7
25	37.2	37.8	45.4	47.4
32	34.3	35.2	42.0	47.2
40	32.8	34.1	41.3	44.3
50	37.2	37.1	43.1	49.7
63	36.9	37.5	43.5	51.6
80	33.7	36.4	39.9	42.4
100	32.4	31.7	35.9	39.8
125	32.2	34.2	38.6	41.8
160	25.3	27.6	33.6	39.1
200	22.4	23.5	38.1	37.4
250	31.7	31.7	40.4	41.3
315	21.1	21.9	30.6	34.7
400	18.2	19.9	34.2	33.8
500	18.1	21.1	33.1	34.2
630	12.3	23.3	34.3	34.1
800	12.1	17.6	31.0	32.5
1000	12.1	12.1	29.0	32.4
1250	9.9	10.4	37.0	32.9
1600	8.3	9.6	31.4	39.1
2000	7.0	8.5	26.0	34.7
2500	6.4	8.5	23.4	31.0
3150	6.0	8.0	20.0	25.2
4000	6.5	8.8	18.6	21.2
5000	6.9	8.1	16.3	19.0
6300	7.0	7.7	16.5	16.3
8000	7.2	7.9	16.7	13.9
10000	7.2	7.6	13.5	12.7
12500	7.3	7.5	12.0	10.8
16000	7.2	7.4	9.2	9.0
20000	7.5	7.5	8.3	8.2
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4.1.2 R-21

The data for the test rooms 21 A, B, and C and the main area are given in table 2. The noise levels in the test rooms are practically negligible, and all meet the ANSI standard for the maximum permissible ambient noise level (MPANL) for ears not covered (ANSI S3.1-1999) with one exception. The noise level in R-21 B at 250 Hz was 22.5 dB, which is slightly higher than the MPANL standard of 16 dB for testing in the 250- to 8000-Hz frequency range but low enough for frequencies from 500 to 8000 Hz. This represents an isolated peak in the noise levels, as the surrounding frequencies are not as high. While the noise in R-21 is slightly higher in the lower frequencies, it is low enough to test sounds in the 500- to 800-Hz range. The use of lighting increases the overall noise level slightly.

Table 2. R-21 – Background noise levels (L_{eq} dB).

Band (Hz)	**R-21A**	**R-21B**	**R-21C**	**R-21**	
				lights off	**lights on**
A-wtd	**18.7**	**19.9**	**20.3**	**22.8**	**24.1**
Linear	58.8	36.4	44.3	52.5	59.1
20	49.5	17.4	38.4	47.8	55.7
25	33.3	16.7	25.7	31.6	37.4
32	29.5	23.9	17.2	30.1	33.5
40	28.4	24.2	17.8	29.1	32.4
50	29.8	20.7	20.4	39.6	40.5
63	32.9	18.1	18.0	32.7	36.5
80	26.7	17.5	16.7	27.5	33.6
100	18.9	16.2	12.3	29.9	33.7
125	20.3	18.7	12.0	29.6	35.7
160	9.9	16.1	15.6	20.3	24.9
200	6.6	9.2	15.0	13.3	17.3
250	7.2	22.5	10.9	12.5	15.1
315	7.0	9.5	9.1	8.8	11.7
400	8.1	13.3	14.9	10.1	11.9
500	9.9	12.4	14.3	12.3	8.5
630	< 5 dB	5.8	12.6	11.2	7.4
800	< 5 dB	5.0	10.1	9.4	6.4
1000	< 5 dB	6.1	6.5	8.8	7.2
1250	< 5 dB	< 5 dB	7.9	8.1	5.6
1600	< 5 dB	< 5 dB	5.6	9.3	6.7
2000	< 5 dB	< 5 dB	5.5	8.4	7.1
2500	4.9	< 5 dB	6.0	8.9	7.5
3150	5.5	4.9	6.5	8.6	6.6
4000	6.0	5.6	7.1	9.0	7.0
5000	6.5	6.3	7.4	8.4	7.1
6300	6.9	6.7	7.7	8.5	7.7
8000	7.1	6.9	7.8	9.1	8.6
10000	7.2	7.0	7.8	9.4	10.5
12500	7.1	7.1	7.7	8.2	8.9
16000	7.1	7.0	7.7	7.6	7.8
20000	7.2	7.2	7.7	7.4	7.5
Date/Time	7/9/03 2:25 PM	7/7/03 11:56 AM	6/6/03 2:25 PM	7/9/03 2:12 PM	7/7/03 2:12 PM

4.1.3 R-29 and R-30

The noise levels are reported in table 3. In all four test spaces, the ambient noise level is less than 20 dB SPL A-wtd and meets the MPANL standards given in (ANSI S3.1-1999) for ears not covered.

Table 3. R-29 and R-30 – background noise levels (L_{eq} dB).

Band (Hz)	**R-29C**	**R-29D**	**R-30A**	**R-30B**
A-wtd	**18.1**	**16.8**	**19.9**	**17.4**
Linear	48.7	53.8	45.4	49.8
20	40.8	40.0	34.4	38.4
25	42.2	29.5	36.9	39.7
32	38.6	30.9	35.1	32.3
40	27.3	23.7	28.4	26.8
50	25.3	19.8	27.8	26.3
63	19.9	16.9	21.7	27.7
80	12.1	11.8	14.7	27.2
100	16.0	9.9	16.9	13.8
125	24.3	< 5 dB	18.3	18.5
160	14.3	5.7	5.7	< 5 dB
200	11.8	< 5 dB	8.7	< 5 dB
250	7.8	6.5	23.4	4.6
315	< 5 dB	< 5 dB	< 5 dB	< 5 dB
400	< 5 dB	< 5 dB	< 5 dB	< 5 dB
500	4.6	< 5 dB	< 5 dB	< 5 dB
630	< 5 dB	< 5 dB	< 5 dB	< 5 dB
800	< 5 dB	< 5 dB	< 5 dB	< 5 dB
1000	4.7	< 5 dB	< 5 dB	< 5 dB
1250	5.3	< 5 dB	< 5 dB	< 5 dB
1600	< 5 dB	< 5 dB	< 5 dB	< 5 dB
2000	< 5 dB	< 5 dB	< 5 dB	< 5 dB
2500	4.6	< 5 dB	4.5	< 5 dB
3150	5.2	4.9	4.9	5.0
4000	5.7	5.7	6.0	5.8
5000	6.4	6.2	6.4	6.4
6300	6.7	6.7	6.7	6.6
8000	6.9	6.8	7.0	6.8
10000	6.9	6.9	7.2	7.0
12500	7.0	6.9	7.3	7.0
16000	7.0	6.9	7.3	7.1
20000	7.0	7.0	7.9	10.6
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4.1.4 HES

The noise levels are presented in table 4. These levels meet or approximate the MPANLs for ears covered. Measurements were taken during the summertime with the AC system operating at its highest setting. The lighting system made a very slight increase in the noise levels. It was necessary, however, to retake the measurements a number of times because vehicles and explosions could be heard outside. The inherent ambient noise level of this very large space is low but quite susceptible to outside noises because of insufficient building isolation.

Table 4. HES – background noise levels (L_{eq} dB).

Band (Hz)	**Center**		**Chair**	
	Lights off	**Lights on**	**Lights off**	**Lights on**
A-wtd	**27.7**	**29.3**	**25.0**	**27.8**
Linear	58.7	59.0	55.9	56.7
20	49.3	49.5	43.7	47.1
25	44.0	44.7	40.2	41.9
32	45.9	44.1	41.2	41.4
40	41.9	43.3	39.9	41.1
50	39.8	39.4	39.1	44.2
63	44.5	44.6	40.3	48.2
80	41.8	42.5	36.1	35.6
100	31.8	32.9	27.8	30.5
125	29.7	30.4	28.1	36.0
160	22.7	23.3	19.9	22.3
200	22.7	22.8	18.5	21.1
250	22.1	22.5	19.1	22.5
315	19.5	20.1	20.6	19.9
400	18.0	18.4	17.9	16.2
500	17.5	18.0	14.0	14.0
630	15.3	16.0	12.6	10.6
800	14.8	15.6	9.6	8.3
1000	12.5	14.1	8.8	10.5
1250	11.8	13.8	9.9	10.2
1600	11.3	15.2	8.8	9.2
2000	10.3	15.4	7.4	7.5
2500	9.7	14.1	7.5	7.3
3150	8.3	15.2	7.5	7.4
4000	8.6	12.9	7.0	7.5
5000	8.9	14.5	7.1	7.3
6300	8.8	12.7	7.2	7.4
8000	8.0	11.0	7.4	7.4
10000	7.8	9.6	7.3	7.3
12500	7.6	8.6	7.3	7.3
16000	7.3	7.9	7.2	7.2
20000	7.3	7.6	7.3	7.3
Date and Time	7/24/03 12:43 PM	7/24/03 12:44 PM	7/24/03 12:48 PM	7/24/03 12:46 PM

4.2 Reverberation Time Measurements

Tables 5 through 11 give the T20 and T30 estimates of RT60 for both the broadband and the one-third octave bands. Because of the limitations of the digital filters used in this study, it was not possible to measure very short reverberation times. This minimum time varies from 20 ms to 1.5 s, depending on the frequency band being measured. When the estimate of RT60 was less than this minimum, the minimum is reported here. Similarly, because a 20- or 30-dB drop was not always observed in all sub-bands, the meter did not always give estimates for every band. When this is true, no estimate is given. Specifically, it was very difficult to get estimates of RT60 in the anechoic chamber (R-21C), and therefore, these measurements should be interpreted with caution. Nevertheless, it appears that this room is anechoic for frequencies above 250 Hz. However, there is some evidence of a vibration near 63 Hz because of vibrations of the metal floor crate.

Table 5. R-5 – T20 and T30 estimates of RT60 measured from the center of the speaker array with the sound source positioned in two room locations, corner and side (RT60 estimates given for both broadband and one-third octave bands).

Impulse/microphone location	**R-5 corner**		**R-5 side**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**0.49**	**0.48**	**0.45**	**0.43**
100	--.--	0.46	0.22	0.25
125	0.49	--.--	0.37	0.27
160	0.40	0.40	0.35	0.18
200	0.41	0.38	0.43	0.57
250	0.35	0.37	0.51	0.56
315	0.56	0.62	0.56	0.38
400	0.48	0.44	0.44	0.50
500	0.41	0.41	0.39	0.37
630	0.42	0.52	0.39	0.31
800	0.30	0.36	0.28	0.31
1000	0.44	0.42	0.29	0.32
1025	0.40	0.36	0.46	0.50
1600	0.40	0.37	0.40	0.42
2000	0.36	0.24	0.40	0.41
2500	0.43	0.46	0.40	0.39
3150	0.47	0.49	0.44	0.41
4000	0.48	0.38	0.45	0.37
5000	0.49	0.41	0.47	0.44
6300	0.46	0.44	0.46	0.37
8000	0.53	0.43	0.42	0.34
10000	0.41	0.38	0.42	0.38
12500	0.34	0.30	0.33	0.32
16000	0.28	0.28	0.27	0.22
20000	0.23	0.23	0.22	0.19
Date and Time	6/6/03 1:26 PM		6/6/03 1:47 PM	

Table 6. R-21A and R-21B: T20 and T30 estimates of RT60 measured in the center of the room with the sound source positioned in a corner (RT60 estimates given for both broadband and one-third octave bands).

Impulse/microphone	**R-21A**		**R-21B**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**--.--**	**0.33**	**0.88**	**0.89**
100	0.62	0.37	--.--	--.--
125	0.76	0.72	--.--	0.79
160	0.46	0.33	0.94	0.83
200	1.03	0.46	1.23	1.26
250	0.35	0.18	0.95	1.02
315	0.45	0.23	1.26	0.93
400	0.44	0.29	1.06	1.19
500	0.48	0.43	0.95	1.10
630	0.34	0.24	1.00	0.76
800	0.28	0.22	0.89	0.83
1000	0.35	0.14	0.82	0.84
1025	0.26	0.11	0.98	0.98
1600	0.29	0.18	0.82	0.84
2000	0.37	0.26	0.81	0.75
2500	0.27	0.13	0.83	0.90
3150	0.20	0.13	0.70	0.83
4000	0.15	0.11	0.74	0.71
5000	0.14	0.11	0.64	0.58
6300	0.14	0.14	0.66	0.66
8000	0.12	0.11	0.56	0.56
10000	0.13	0.10	0.53	0.49
12500	0.12	0.11	0.43	0.42
16000	0.13	0.10	--.--	0.34
20000	0.13	0.10	--.--	--.--
Date and Time	7/9/03 2:48 PM		6/6/03 2:12 PM	

Table 7. R-21C and R-1: T20 and T30 estimates of RT60 measured from the center of the room with the sound source positioned in a corner (RT60 estimates given for both broadband and one-third octave bands).

Impulse/microphone location	**R-21C**		**R-21**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**--.--**	**0.06**	**--.--**	**0.27**
100	< 0.18	< 0.18	0.23	0.24
125	< 0.18	< 0.18	0.24	< 0.18
160	< 0.18	< 0.18	0.21	< 0.18
200	0.12	0.13	0.20	0.14
250	< 0.09	< 0.09	0.29	0.20
315	< 0.09	< 0.09	0.26	0.23
400	< 0.06	< 0.06	0.26	0.17
500	< 0.06	< 0.06	0.14	0.14
630	< 0.06	< 0.06	0.48	0.52
800	0.04	< 0.03	0.44	0.31
1000	--.--	< 0.03	0.43	0.27
1025	--.--	< 0.03	0.52	0.30
1600	--.--	< 0.02	0.36	0.23
2000	--.--	< 0.02	0.31	0.20
2500	--.--	< 0.02	0.38	0.27
3150	--.--	< 0.02	0.24	0.22
4000	--.--	< 0.02	0.34	0.23
5000	--.--	< 0.02	0.27	0.23
6300	--.--	< 0.02	0.25	0.21
8000	--.--	< 0.02	0.32	0.24
10000	--.--	< 0.02	0.26	0.25
12500	--.--	< 0.02	0.22	0.20
16000	--.--	< 0.02	0.19	0.19
20000	--.--	< 0.02	0.17	0.16
Date and Time	7/9/03 3:05 PM		6/6/03 2:57 PM	

Table 8. R-29C and R-29D: T20 and T30 estimates of RT60 measured from the centers of the rooms with the sound source positioned in a corner (RT60 estimates given for both broadband and one-third octave bands).

Location	**R-29C**		**R-29D**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**1.07**	**1.13**	**--.--**	**0.23**
100	--.--	0.42	0.21	0.28
125	0.22	0.19	< 0.18	< 0.18
160	--.--	0.39	< 0.18	< 0.18
200	--.--	1.4	0.19	0.19
250	--.--	0.6	0.12	< 0.90
315	--.--	0.42	< 0.90	< 0.90
400	0.68	0.83	0.09	0.11
500	--.--	1.08	--.--	0.49
630	0.86	1.32	0.48	0.23
800	--.--	0.55	--.--	0.08
1000	0.94	1.12	--.--	0.45
1250	0.86	0.63	--.--	0.41
1600	0.84	0.79	--.--	--.--
2000	0.99	1.21	--.--	--.--
2500	1.17	1.31	--.--	0.17
3150	1.30	1.65	--.--	0.15
4000	1.14	1.27	--.--	0.12
5000	1.09	1.27	0.13	0.10
6300	0.85	0.92	0.27	0.08
8000	0.67	0.67	0.11	0.09
10000	0.56	0.58	0.09	0.09
12500	0.47	0.49	0.22	0.10
16000	--.--	0.36	0.09	0.08
20000	--.--	0.33	0.08	0.08
Date and Time	6/18/03 10:49 AM		6/20/03 5:35 PM	

Table 9. R-30A and R-30B: T20 and T30 estimates of RT60 measured from the centers of the rooms with the sound source positioned in a corner (RT60 estimates given for both broadband and one-third octave bands).

Location	**R-30A**		**R-30B**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**--.--**	**0.49**	**0.65**	**0.66**
100	0.25	0.25	--.--	0.18
125	0.22	0.30	0.49	0.25
160	0.22	0.30	--.--	< 0.18
200	0.23	0.24	--.--	0.63
250	0.42	0.41	--.--	0.48
315	0.24	0.30	0.53	0.58
400	0.26	0.24	--.--	0.58
500	0.38	0.29	1.52	0.46
630	0.33	0.30	0.58	0.46
800	0.31	0.38	0.61	0.48
1000	0.54	0.48	0.56	0.49
1250	0.39	0.47	0.60	0.60
1600	0.48	0.54	0.52	0.52
2000	0.47	0.48	0.81	0.70
2500	0.57	0.57	0.65	0.58
3150	0.52	0.51	0.68	0.72
4000	0.52	0.53	0.64	0.60
5000	0.48	0.42	0.62	0.63
6300	0.48	0.41	0.55	0.57
8000	0.42	0.38	0.48	0.54
10000	0.34	0.34	0.40	0.41
12500	0.31	0.32	0.37	0.39
16000	0.25	0.26	--.--	0.32
20000	0.21	0.19	--.--	--.--
Date and Time	7/25/03 3:29 PM		6/18/03 11:18 AM	

Table 10. Ensuing measurements of the reverberation times in R-30A and R-30B as taken with the 01dB[8] meter.

	30A	**30B**
250 Hz	0.31	0.46
500 Hz	0.27	0.43
1000 Hz	0.33	0.47
2000 Hz	0.30	0.54
4000 Hz	0.26	0.51

Table 11. HES: T20 and T30 estimates of RT60 measured from the listener position of two experimental setups. (In both cases, the sound source was located next to the screen. RT60 estimates given for both broadband and one-third octave bands.)

Impulse/microphone location	**Center**		**Side**	
Band	**T30**	**T20**	**T30**	**T20**
Broadband	**--.--**	**0.56**	**--.--**	**0.48**
100	0.51	0.42	0.51	0.37
125	0.65	0.50	--.--	0.40
160	0.64	0.38	0.83	0.56
200	0.58	0.73	0.44	0.39
250	0.53	0.38	0.55	0.42
315	0.49	0.41	0.27	0.36
400	0.35	0.21	0.46	0.27
500	0.36	0.38	0.30	0.32
630	0.46	0.21	0.29	0.28
800	0.42	0.36	0.33	0.29
1000	0.41	0.39	0.40	0.32
1025	0.39	0.39	0.48	0.43
1600	0.46	0.36	0.35	0.28
2000	0.45	0.46	0.37	0.43
2500	0.43	0.44	0.35	0.39
3150	0.39	0.38	0.40	0.38
4000	0.48	0.48	0.33	0.38
5000	0.46	0.41	0.42	0.43
6300	0.43	0.41	0.41	0.45
8000	0.38	0.41	0.38	0.39
10000	0.39	0.39	0.31	0.25
12500	0.34	0.33	0.27	0.28
16000	0.27	0.26	0.26	0.23
20000	0.24	0.23	0.26	0.27
Date and Time	6/5/03 1:49 PM		6/5/03 1:54 PM	

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[8] 01dB Acoustics Vibration®, which is a registered trademark, is the name of the company.

Decay profiles were generated independently for broadband and narrowband sounds. Because the broadband level was A-weighted, it was less influenced by the decay rates of the lower frequencies. So, although some of the sub-bands below 500 Hz may have had a slower decay rate, their influence on the overall level was reduced, and therefore, the broadband RT60 was shorter than that of some of the one-third octave bands.

There is also the paradox that in some cases, we were able to obtain RT60 estimates for all the sub-bands and yet not able to get a broadband estimate, as was the case for the T30 estimates of RT60 in R-21. This is probably because of a failure to sample the average broadband level at enough points along the timeline to generate an estimate within the CEL's accuracy parameters. Repetition of this particular measurement in R-21 gave very consistent T20 estimates of the broadband RT60, and inspection of the decay profiles suggests that these estimates are reasonable.

Also, because the ambient noise levels may have been high for a particular band, the decay profile of the impulse noise may be affected by ambient noise, thus artificially increasing the RT60 estimate. It does not appear that this occurred often. Inspection of the decay profiles suggests that it did happen in the measurement of the 200-Hz sub-band in R-21A and that the T20 measurement more accurately describes the decay. In contrast, the discrepancies observed for R-21B at 315 and 630 Hz seem to be attributable to fluctuations in the decay profile which artificially decreased the T20 estimate. This is also true of both measurements of the 160-Hz sub-band in HES.

No measurements had previously been made of R-5 and HES. Earlier acoustical data for the rest of the rooms were approximated by these new measurements except that the reverberation times for R-30A and R-30B were slightly longer. Previously, it was recorded that both rooms had reverberation times of 0.4 s. Because we were concerned about the discrepancy between the current reverberation time measurements and those taken previously, we obtained an 01dB Symphonie sound measurement system, and using the dBBATI32 building acoustics package, we re-measured R-30A and R-30B. We recorded reverberation times for the five octave bands between 250 and 4000 Hz, and these are shown in table 10. This time, the reverberation times measured for R-30A were lower than those recorded previously—approximately 0.3 s. However, those measured for R-30B were slightly higher, ranging from 0.43 to 0.54 s.

The differences in the two measurement methods are probably not significant. These rooms are large and during measurement it, was noted that a change in the location of the trigger noise could affect the measurements considerably. In both cases, the numbers reported here are from the most representative of several measurements. It is also unlikely that the reverberation times of these rooms have changed significantly since the previous measurement. Changes of equipment housed in these rooms may explain differences. It is also possible that previously, measurements were taken in an auspicious location and were artificially low.

4.3 Room Reflections

4.3.1 R-5

Recordings were made of the impulse responses to signals played from each of the four loudspeakers on the cube as it is positioned in the diagram shown in appendix A, figure A-1. Graphs of the waveforms are shown in figures 5 through 8. Table 12 gives a description of the reflections observed and their sources. The primary sources of reflected energy are the three nearest walls and the floor. The cube is situated so that it is approximately but not exactly equidistant from three of the walls. Therefore, multiple temporally contiguous reflections occur at ~17 and 22 ms, and their exact source surfaces are ambiguous. However, none of the early reflections observed are likely to influence localization, as all were more than 15 dB below the initial signal level.

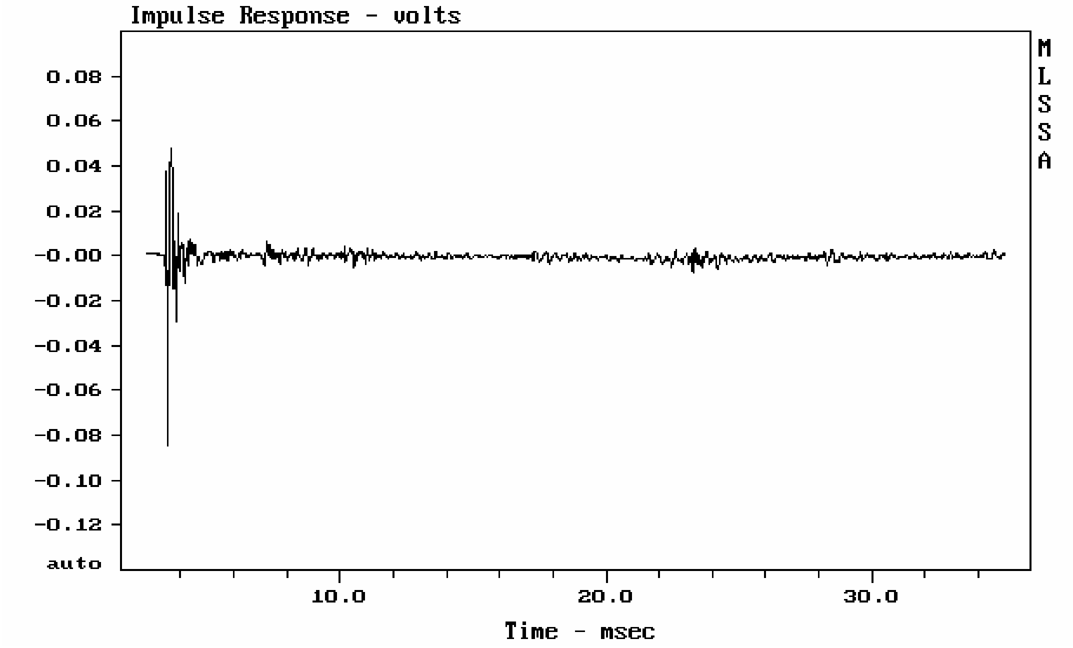

Figure 5. Impulse response recorded in R-5 when the test signal was played from loudspeaker 1.

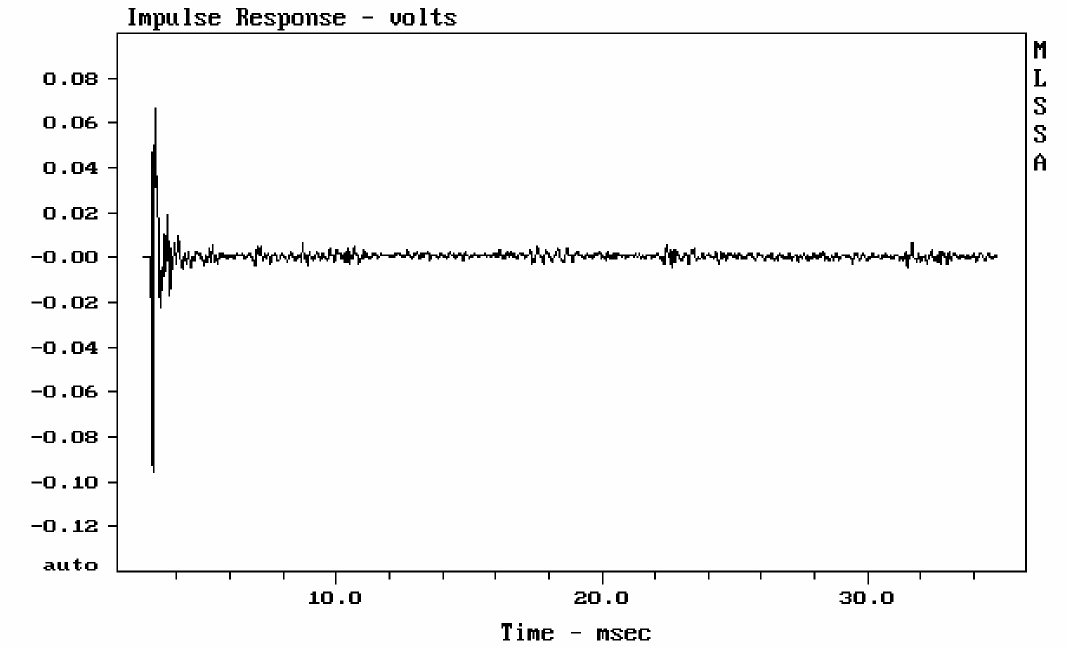

Figure 6. Impulse response recorded in R-5 when the test signal was played from loudspeaker 2.

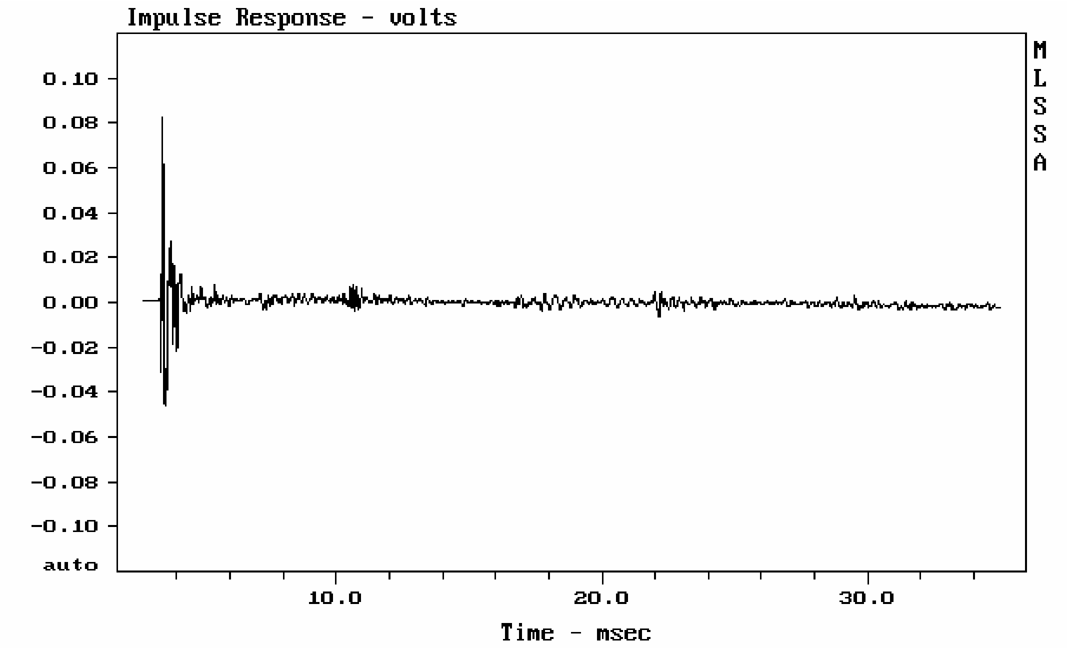

Figure 7. Impulse response recorded in R-5 when the test signal was played from loudspeaker 3.

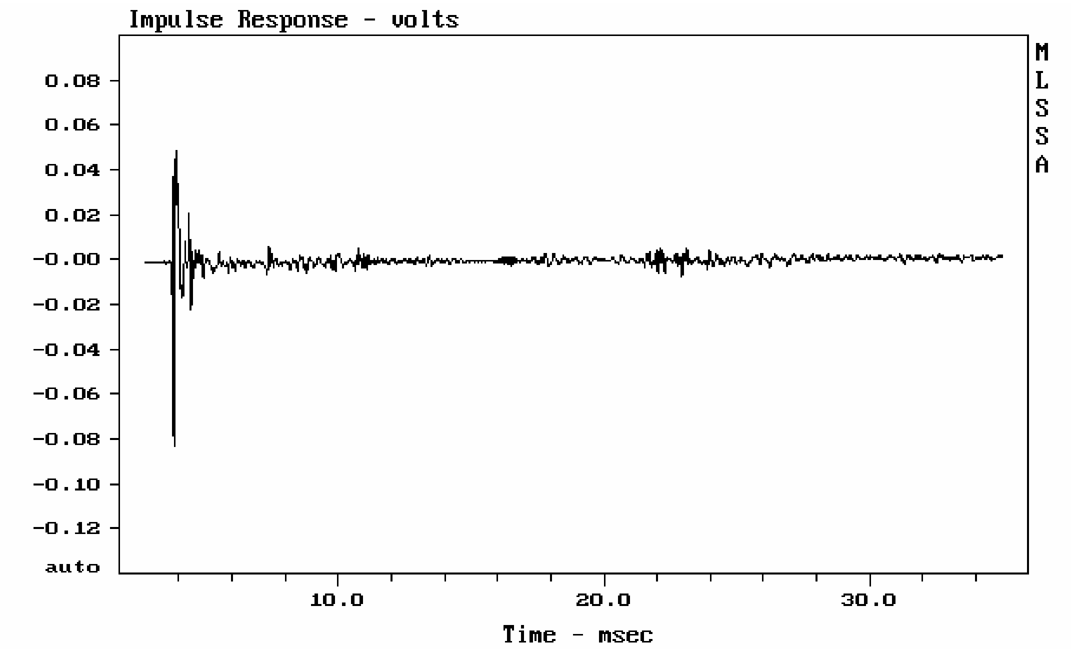

Figure 8. Impulse response recorded in R-5 when the test signal was played from loudspeaker 4.

Table 12. Description of early reflections and their likely sources as observed in R-5.

Loudspeaker Position	Time of Arrival (ms)	Distance traveled (cm)	Major reflective surfaces	Ratio of reflection to noise (dB)
Any	7.2	220	Floor	-23
	11	359	Ceiling	-24
1	17	579	Wall 1	-25
	22	735	Wall 2	-21
			Wall 3	-21
	28	934	Wall 4	-25
2	17	579	Wall 1	-26
			Wall 2	-26
	22	735	Wall 3	-26
	32	1090	Wall 4	-24
3	22	735	Wall 1	-21
	17	579	Wall 2	-25
			Wall 3	-25
4	22	735	Wall 1	-16
			Wall 2	-19
	17	579	Wall 3	-25

4.3.2 R-21

The robotic arm was used to move the loudspeaker to the four positions shown in appendix A, figure A-2. Graphs of the waveforms are shown in figures 9 through 12 and a description of the early reflections and their sources is given in table 13. R-21 was being used to house a number of objects that could have caused reflections, but the primary sources of reflections appeared to be the two adjoining walls (labeled as wall 1 and wall 2 in the diagram). These reflections were between 11 and 25 dB below the level of the initial signal and are unlikely to affect sound localization. The robotic arm is positioned over a wooden platform that holds a chair and a metal support used to position the listener or to hold an acoustic mannequin. Reflections were observed around 5, 9, and 11 ms, which would be consistent with reflected sound from elements of this platform, but they were not high enough in level to interfere with localization (22 dB below signal level).

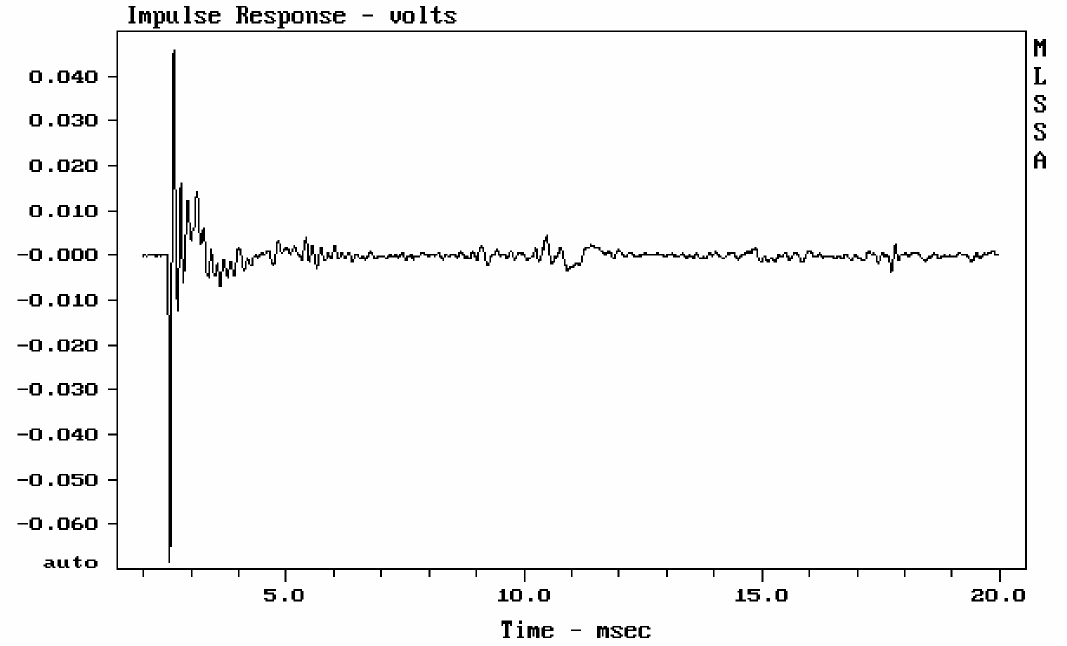

Figure 9. Impulse response recorded in R-21 when the test signal was played from the loudspeaker at position 1.

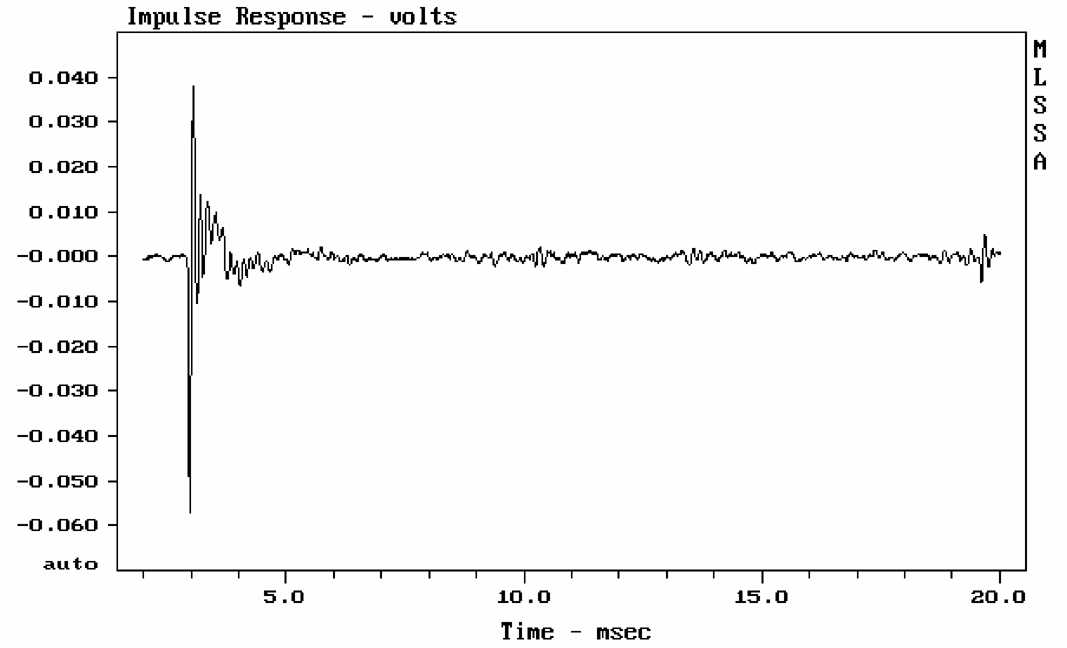

Figure 10. Impulse response recorded in R-21 when the test signal was played from the loudspeaker at position 2.

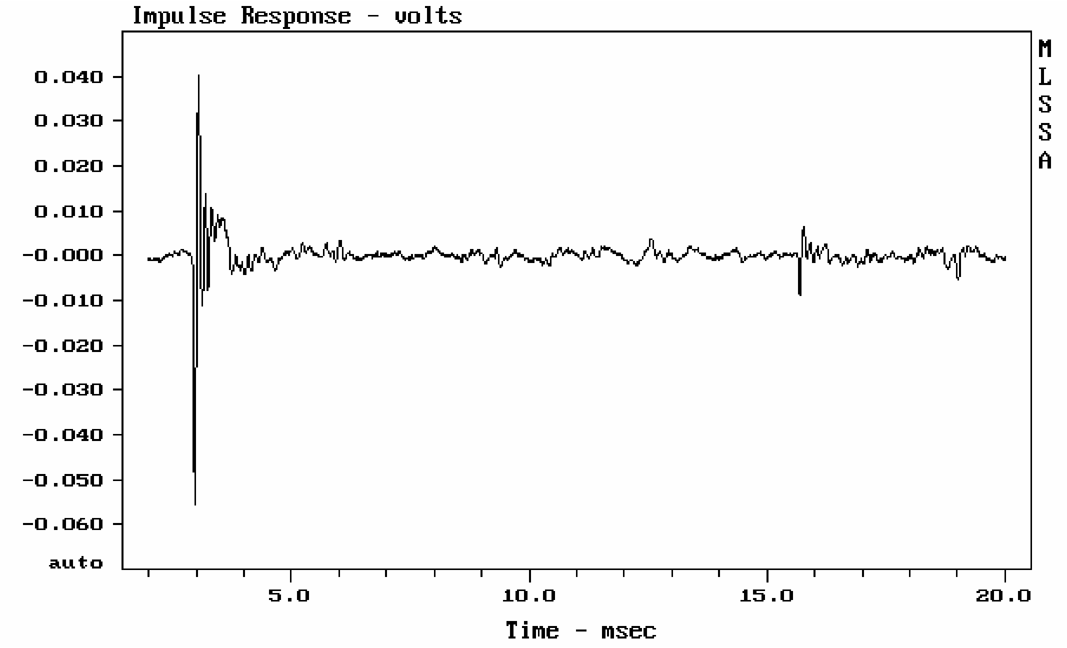

Figure 11. Impulse response recorded in R-21 when the test signal was played from the loudspeaker at position 3.

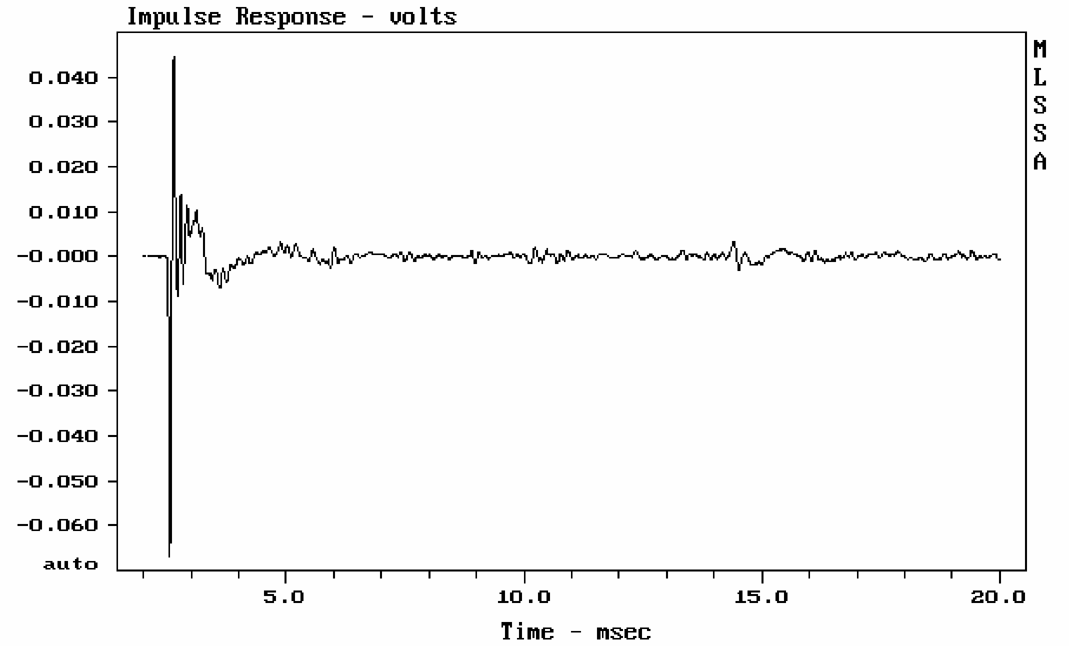

Figure 12. Impulse response recorded in R-21 when the test signal was played from the loudspeaker at position 4.

Table 13. Description of early reflections and their likely sources as observed in R-21.

Loudspeaker Position	Time of Arrival (ms)	Distance traveled (cm)	Major reflective surfaces	Ratio of reflection to noise (dB)
1	5	162	Chair*	-24
	9	303	Platform*	-26
	10	328 & 334	Wall 1 + Ceiling	-23
	11	372	Floor	-19
	18	612	Wall 3	-23
2	13	432	Wall 1	-25
	20	662	Wall 2	-14
3	5	162	Chair	-22
	9	303	Platform	-22
	10	334	Ceiling	-22
	12.5	424	Wall 3	-22
	15	516	Wall 1	-11
	19	637	?	-14
4	5	162	Chair	-22
	6	201	?	-23
	10	334	Ceiling	-24
	14	474	Wall 2	-23

4.3.3 HES

A recording was taken of the impulse responses to the four loudspeakers shown in appendix A, figure A-5. These are four of 12 loudspeakers on the bottom tier of the chandelier. For discussion purposes, we will refer to them as speakers 1, 2, 3, and 4 as indicated in figure A-5. The graphs of the impulse response recordings are shown in figures 13 through 16, and table 14 summarizes their main features. The largest reflection (at 11 ms) was from the floor and had a level about 14 dB lower than that of the signal. It should have no effect on azimuthal localization because it comes from the same azimuthal direction.

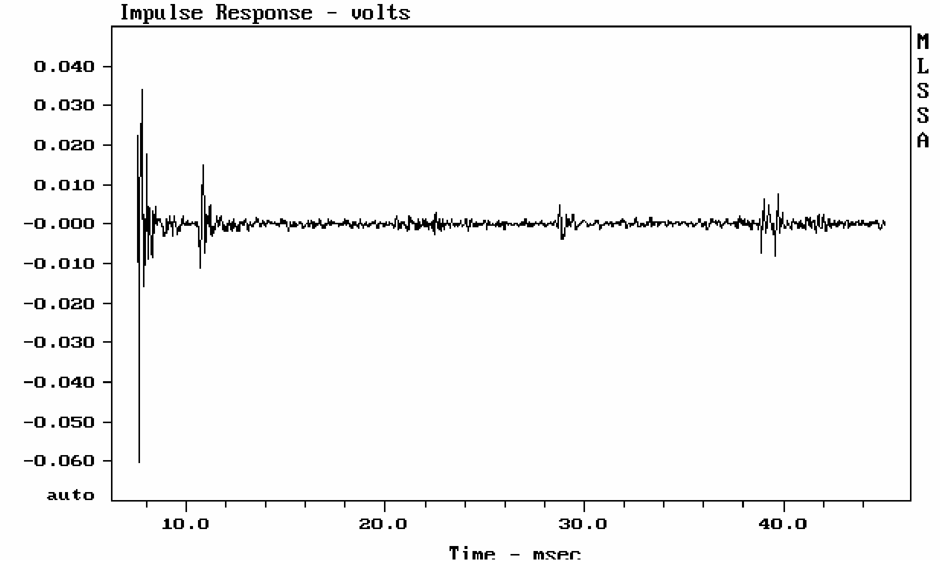

Figure 13. Impulse response recorded in HES when the test signal was played from loudspeaker 1.

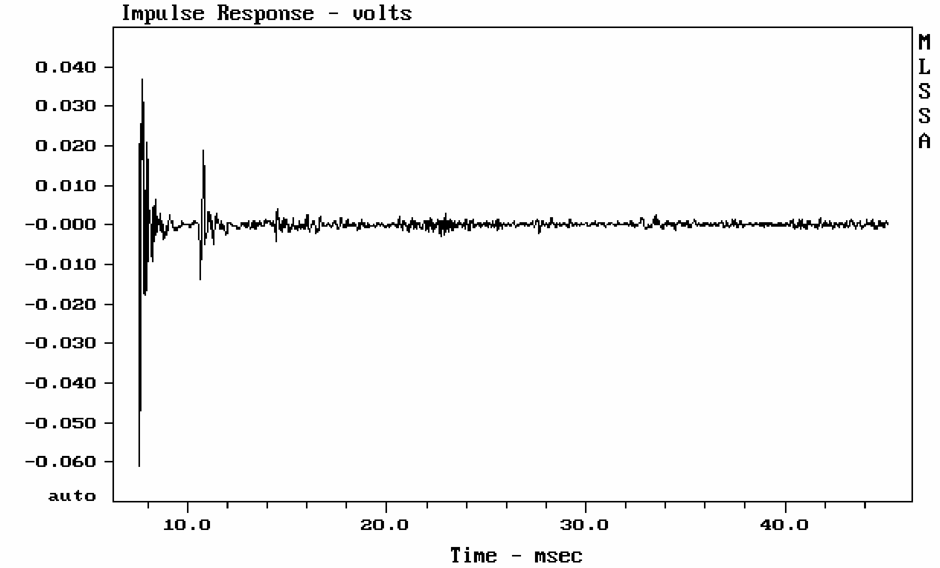

Figure 14. Impulse response recorded in HES when the test signal was played from loudspeaker 2.

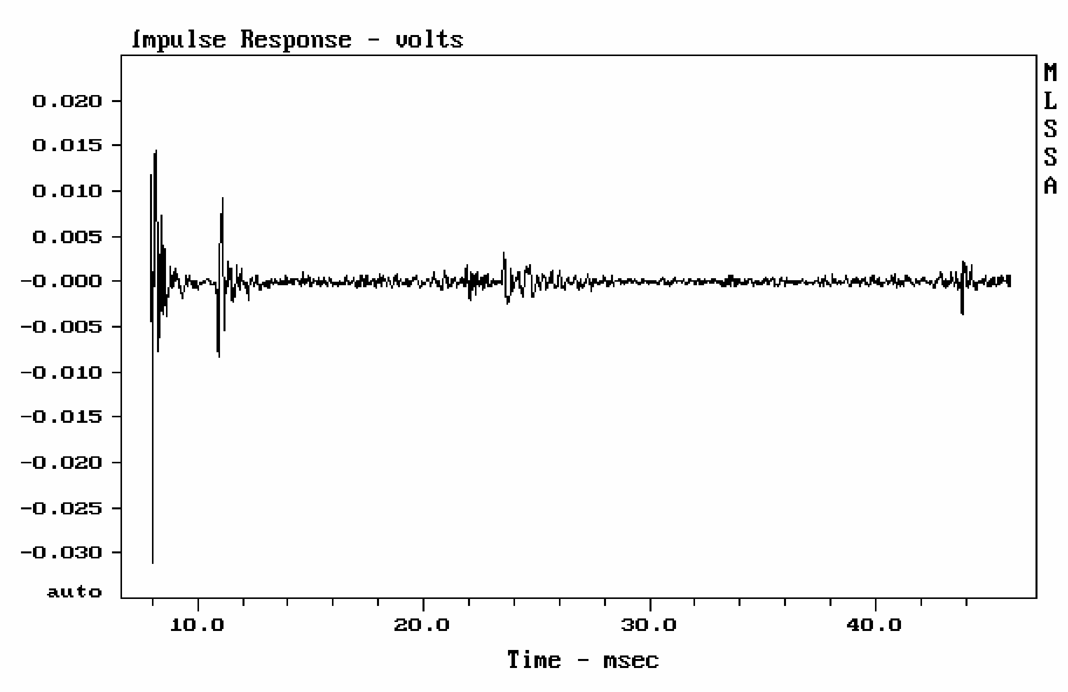

Figure 15. Impulse response recorded in HES when the test signal was played from loudspeaker 3.

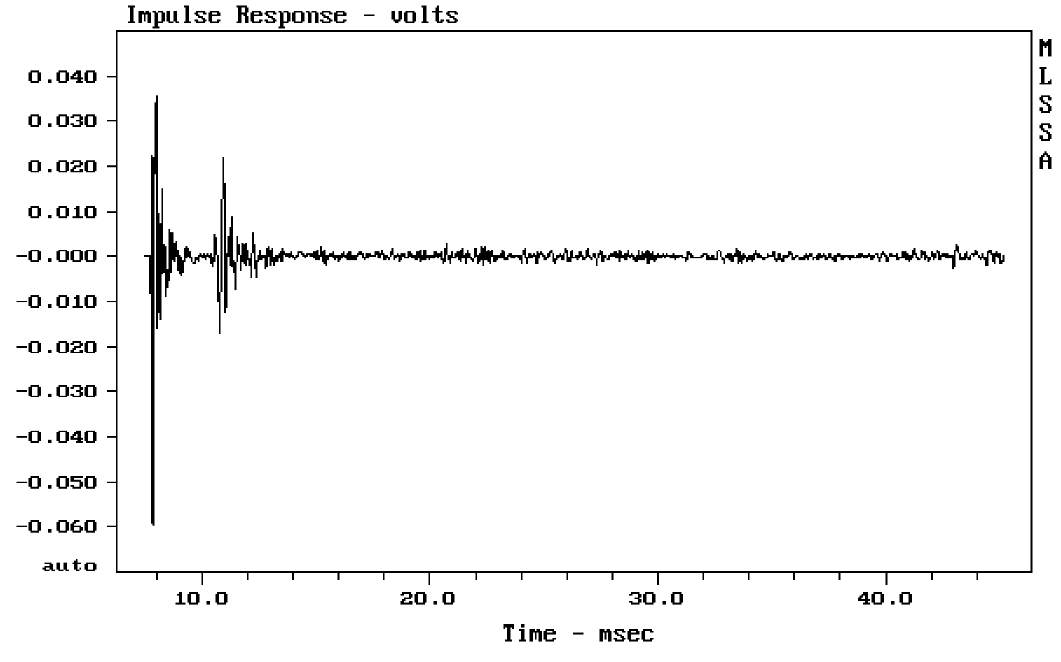

Figure 16. Impulse response recorded in HES when the test signal was played from loudspeaker 4.

Table 14. Description of early reflections and their likely sources as observed in HES.

Loudspeaker Position	Time of Arrival (ms)	Distance traveled (cm)	Major reflective surfaces	Ratio of reflection to noise (dB)
1	11	374	Floor	-14
	23	771	Screen	-26
	29	972	?	-21
	40	1368	Ceiling	-18
	45	1520	Wall 3/Door	-27
2	11	374	Floor	-13
	23	771	?	-24
3	11	374	Floor	-11
	22	738	?	-24
	24	805	Wall 3/Door	-24
	44	1352	Screen	-18
4	11	374	Floor	-10
	43	1441	Ceiling	-22

Of principal concern was whether reflections from the walls and screen were affecting sound source location cues. As can be seen in table 14, reflections from the walls nearest loudspeakers 1 and 3 arrive at about 23 or 24 ms. The levels of these reflections were more than 20 dB below those of the signal level and should not affect localization. The graphs for loudspeakers 1 and 3 also show low reflections (>15 dB below initial signal) at around 44 ms. Since these occur more than 30 ms after the initial signal they should appear independent from the initial signal and should not affect localization. However, it is notable that when the signal was played from loudspeaker 3, the reflection from the screen opposite it was higher than the one from the door behind it.

The reflections observed should not be problematic because they were more than 15 dB below that of the direct signal and/or occurred beyond the period of temporal integration. This is in conflict with informal reports suggesting that reflections coming from the screen were greatly disrupting localization. Data from some previous experiments showed that listeners experienced significant disruption of auditory localization ability when they were facing the screen. When the listeners were facing the 90-degree direction, this problem was not present. Therefore, to determine the source of these reports, we proposed two possible explanations: 1) although the level and timing of the reflections fall outside the boundaries established by research as affecting localization percept, the low ambient noise and the large size of the space cause them to be perceptually important; and 2) reflections become problematic only at higher sound levels.

In order to determine the potential cause of reported localization errors, sounds were played at 70 dB SPL A-wtd and listeners were recruited to report their perceptions. Listeners were asked to stand in the center of the chandelier while sounds were played from loudspeakers 1 and 3. For half of the trials, the doors were propped open. Listeners had difficulty distinguishing front from back when the sound was played from loudspeaker 3. This was presumably because of reflections from the screen. At times, they reported this as perceiving an echo coming from the direction of the screen. Other times, it was reported as being "confusing". When the sound was played from loudspeaker 1, they reported more difficulty with localization if the doors were closed.

To test the effect of level on reflections, recordings were made of the responses to two levels of noise, 70 and 83 dB SPL A-wtd. These recordings were made when the doors were open and when they were closed (figures 17 through 24). Table 15 presents a summary of the major reflections observed. A proportional increase in the ratio of direct to reflective sound would be expected with an increase in level. With the possible exception of the reflection that comes from the door when loudspeaker 1 is sounded, the levels observed for reflections did not significantly increase for higher sound levels. Given the reported perceptual experiences of our listeners, it seems that when higher level stimuli are played, they are sensitive to the reflections, even when they are more than 15 dB below the level of direct sound (the highest level measured was 16 dB below the direct signal level). This may be attributable to the unusually low ambient noise in this space. Further, a number of additional reflections coming from other large objects and surfaces within the space may make the localization task even more difficult. These reports and recordings suggest that this space is not ideal for localization research unless we remove the screen and make a number of other acoustical adaptations.

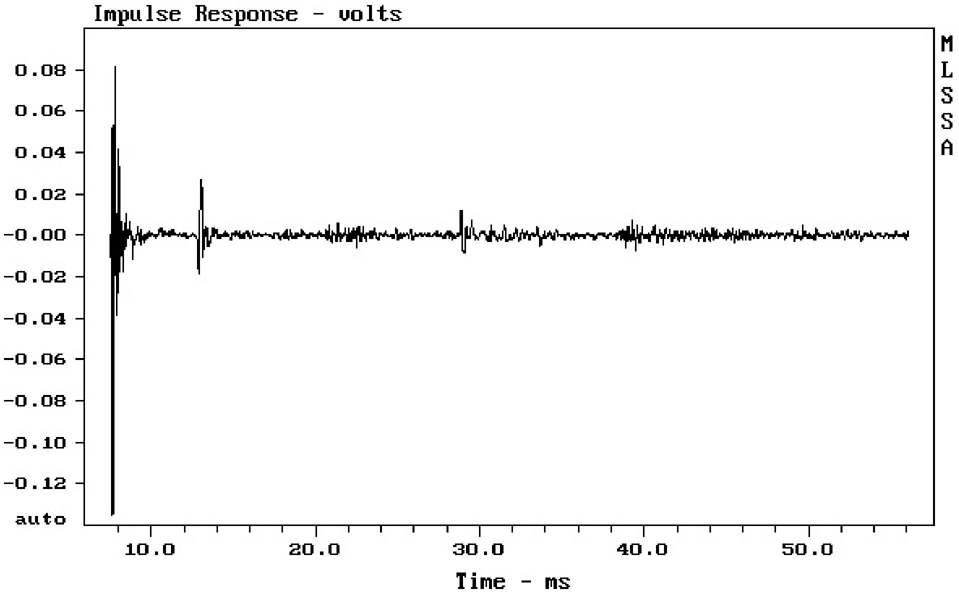

Figure 17. Impulse response recorded in HES when the test signal was played at a level of 70 dB SPL A-wtd from loudspeaker 1 and the doors were open.

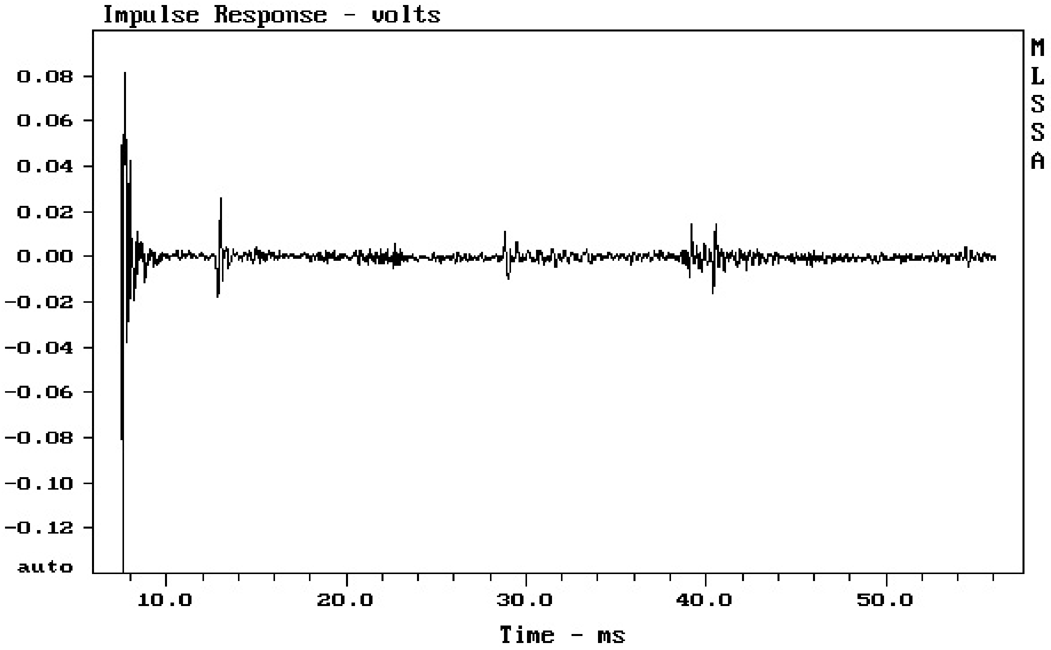

Figure 18. Impulse response recorded in HES when the test signal was played at a level of 70 dB SPL A-wtd from loudspeaker 1 and the doors were closed.

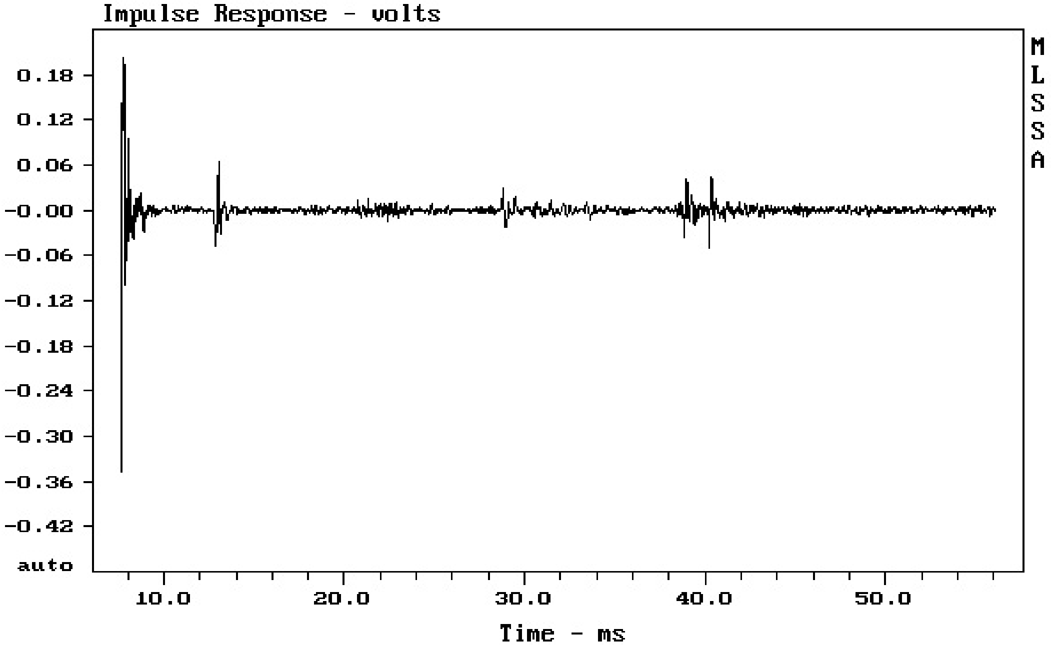

Figure 19. Impulse response recorded in HES when the test signal was played at a level of 70 dB SPL A-wtd from loudspeaker 3 and the doors were open.

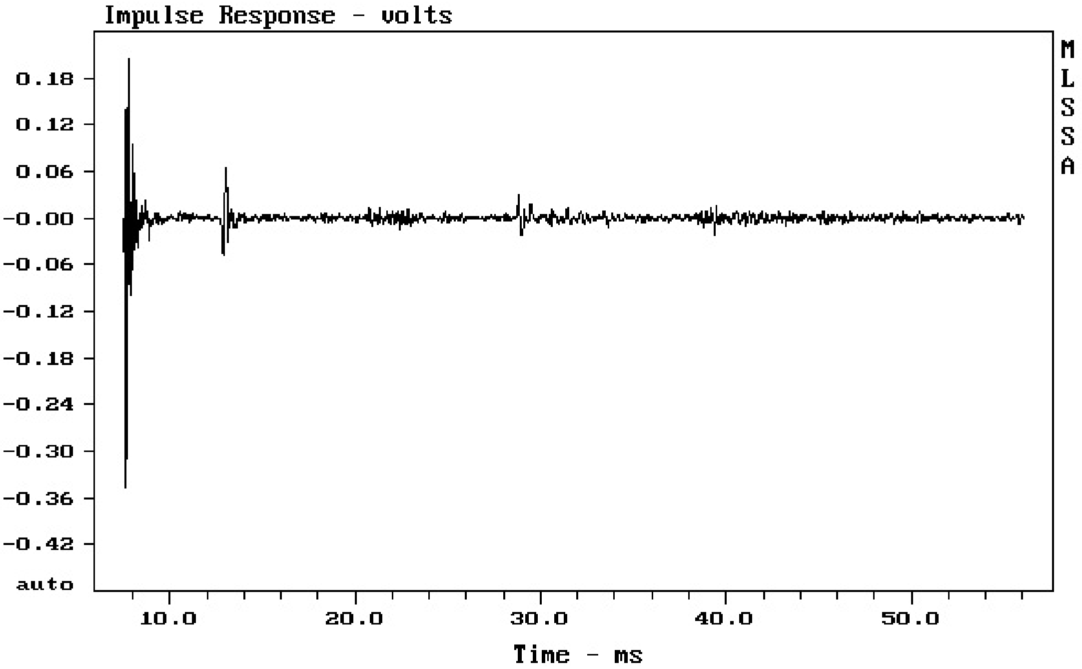

Figure 20. Impulse response recorded in HES when the test signal was played at a level of 70 dB SPL A-wtd from loudspeaker 3 and the doors were closed.

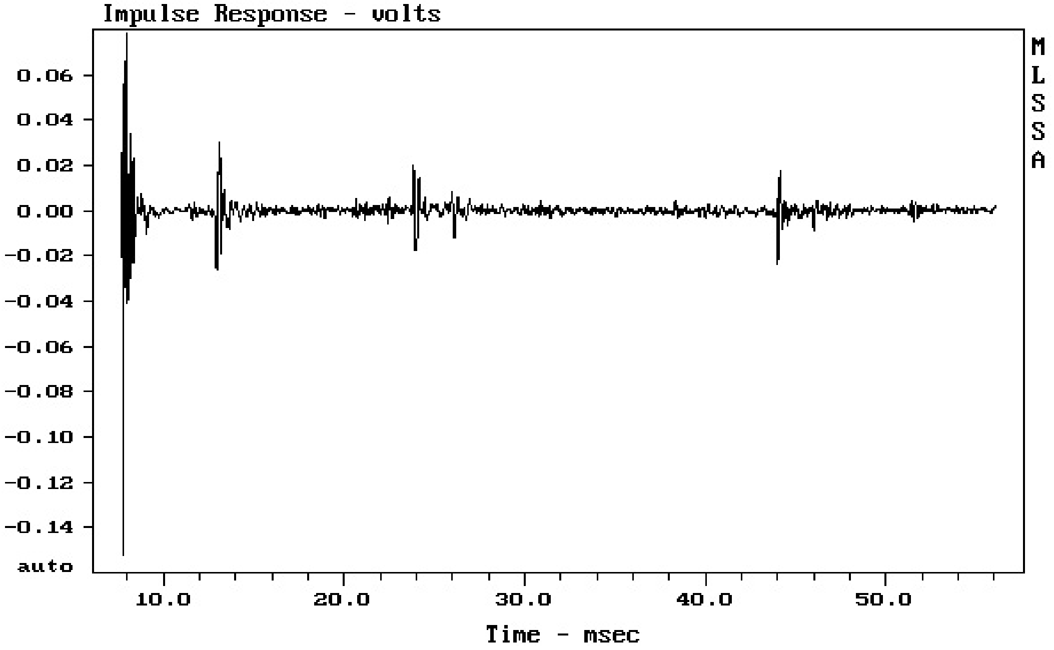

Figure 21. Impulse response recorded in HES when the test signal was played at a level of 83 dB SPL A-wtd from loudspeaker 1 and the doors were open.

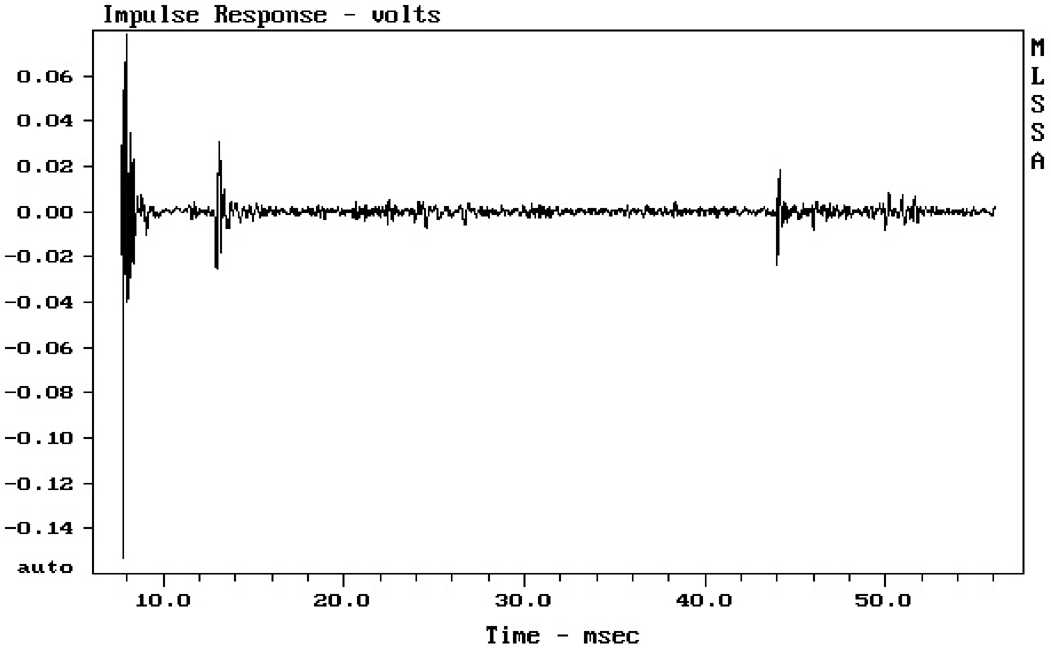

Figure 22. Impulse response recorded in HES when the test signal was played at a level of 83 dB SPL A-wtd from loudspeaker 1 and the doors were closed.

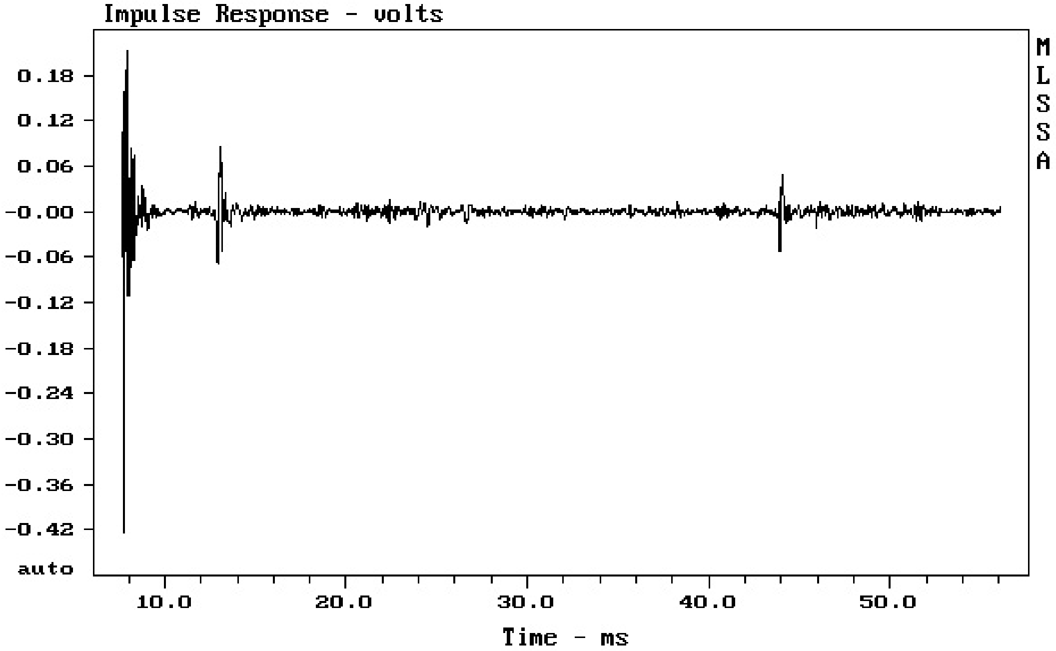

Figure 23. Impulse response recorded in HES when the test signal was played at a level of 83 dB SPL A-wtd from loudspeaker 3 and the doors were open.

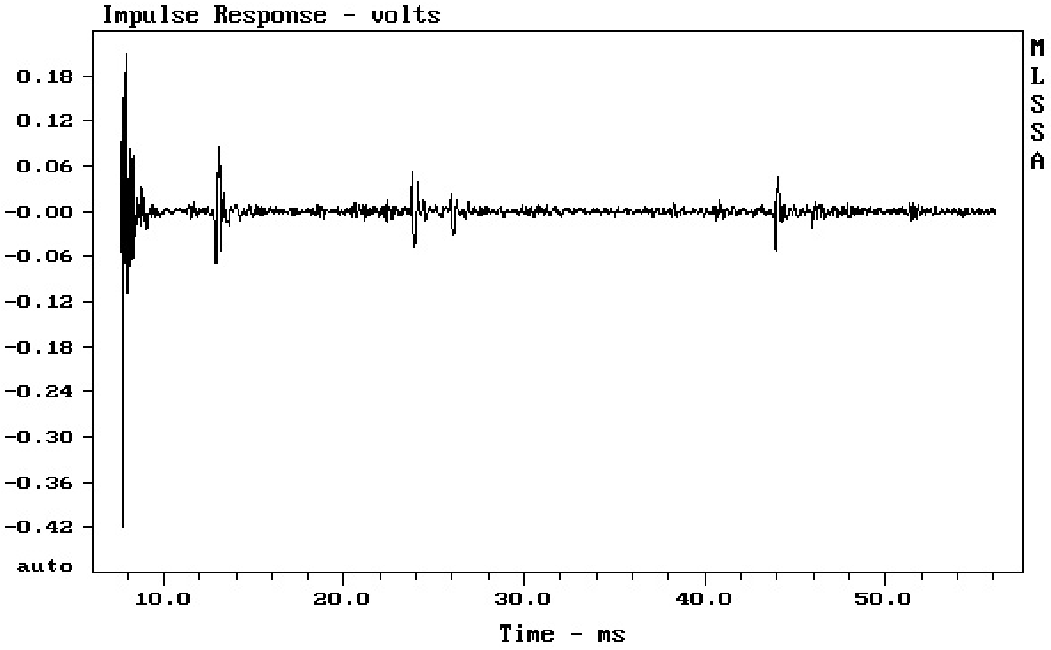

Figure 24. Impulse response recorded in HES when the test signal was played at a level of 83 dB SPL A-wtd from loudspeaker 3 and the doors were closed.

Table 15. Description of early reflections and their likely sources when the signal was played at higher levels from loudspeakers 1 and 3 in HES.

Loudspeaker Position	Time of Arrival (ms)	Distance traveled (cm)	Major reflective surfaces	Noise level			
				70 dB		83 dB	
				Ratio of Reflection to Noise (dB)			
				Door Open	Door Closed	Door Open	Door Closed
1	13	446	Floor	-16	-14.5	-14.5	-14.5
	22.5	772	?	-26	-27.5	-27	-27
	29	995	Screen	-23	-23	-23	-25
	33.5	1149	?			-27	-27
	39	1338	Wall 3/Door	-25	-19.5	-23	-19
	40.5	1389	?		-18		-16
3	13	446	Floor	-15.5	-15.5	-14	-14
	22.5	772	?	-27	-27	-29	-28
	24.5	840	Wall 3/Door	-26	-18	-26.5	-18.5
	27	926	?	-27	-23	-29	-23
	44	1509	Screen	-16	-16	-18	-18
	46	1578	?	-25	-25	-26	-26
	50	1715	?	-25			
	51	1749	?	-26			
	51.5	1766	?	-27	-30	-28	-28

5. Summary

Ambient noise levels for most of the test spaces met the standards for maximum permissible ambient noise levels (ANSI S3.1-1999). Only R-5 had higher levels. The noise floor in this room needs to be taken into consideration when one is conducting experiments. The use of masking may be appropriate in some cases. The levels in HES are sufficiently low for our auditory tests that are conducted at levels well above the threshold of hearing or with ears covered. The biggest concern in HES is its vulnerability to external sound, which increases the time required to obtain a complete set of experimental data.

Most of the reverberation times measured in this study show relative independence from frequency in the 500- to 4000-Hz range. Their RT60 values ranged from 0.06 to 1.13 s, depending on the specific room. In the anechoic chamber in R-21C, the acoustically absorptive wedges are slowly deteriorating and may compromise the anechoic properties at some future date. This room requires periodic acoustic monitoring to ensure that all parameters remain acceptable.

None of the rooms, with the exception of HES, revealed early or late room reflections that were strong enough to affect direct sound perception at the predetermined listener locations. Only in HES do wall reflections from the screen and the opposite wall affect sound perception if the direct sound exceeds predetermined levels. Based on the collected experimental data, this level is about 70 dB and is additionally dependent on the sound spectrum and auditory characteristics of the listener. Although this can be problematic for some studies, in many experiments, orienting the subject 90 degrees to the screen can mitigate to some degree the impact of this effect.

In conclusion, the use of the HES for spatial sound studies should probably be limited to those using very low level sounds, originating from a very narrow angle of possible directions and positioning the listener in an off-center position. Removing the screen and covering the doors with absorptive material might potentially eliminate the acoustic problems with HES. However, this solution may not be fully successful because of the reflective wall behind the screen and reflections from hard surfaces of the large loudspeaker at the bottom of the screen.

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Appendix A. Room Dimensions and Measurement Points

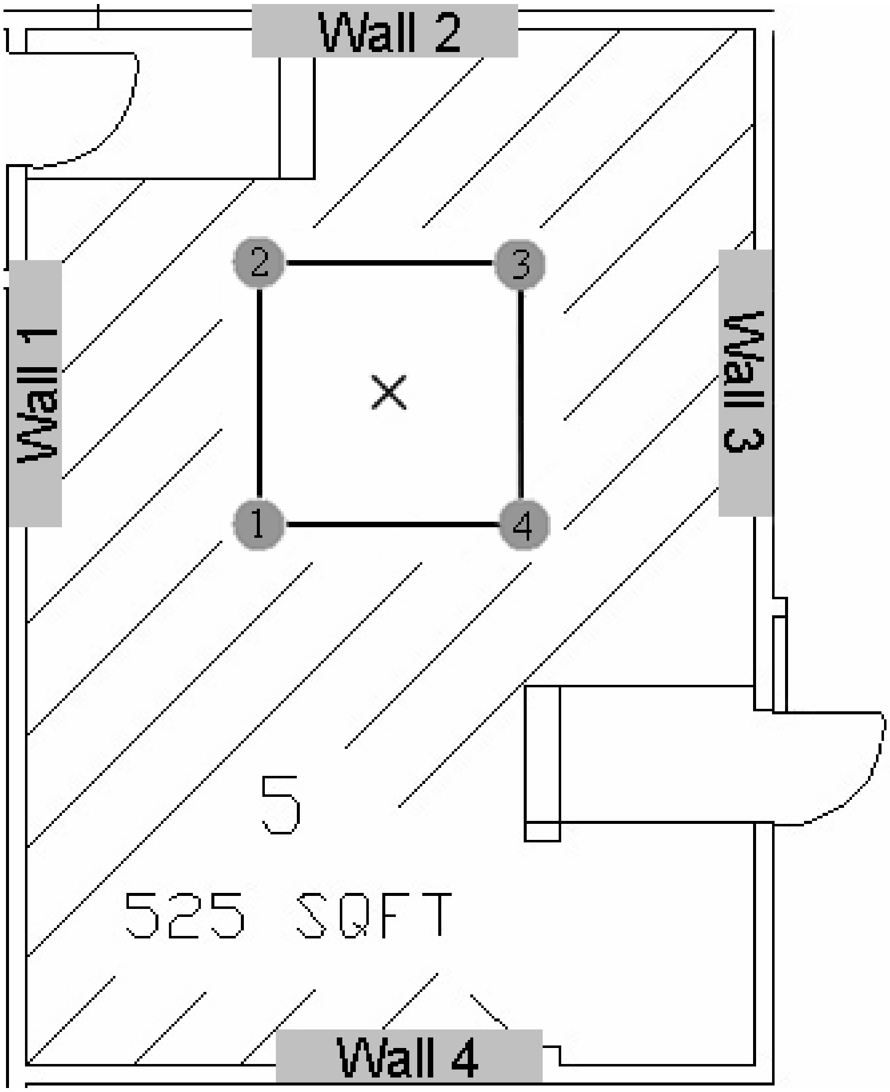

Figure A-1. R-5: Headgear evaluation and assessment room (HEAR).

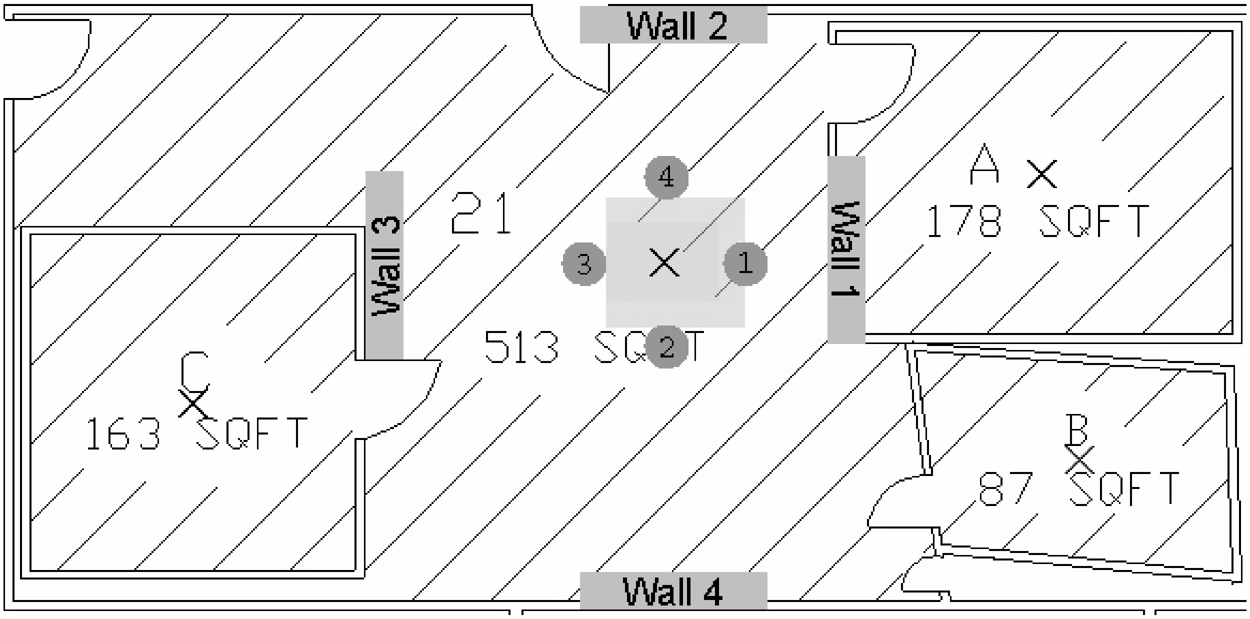

Figure A-2. R-21: Environmental laboratory with HRTF measurement facility.

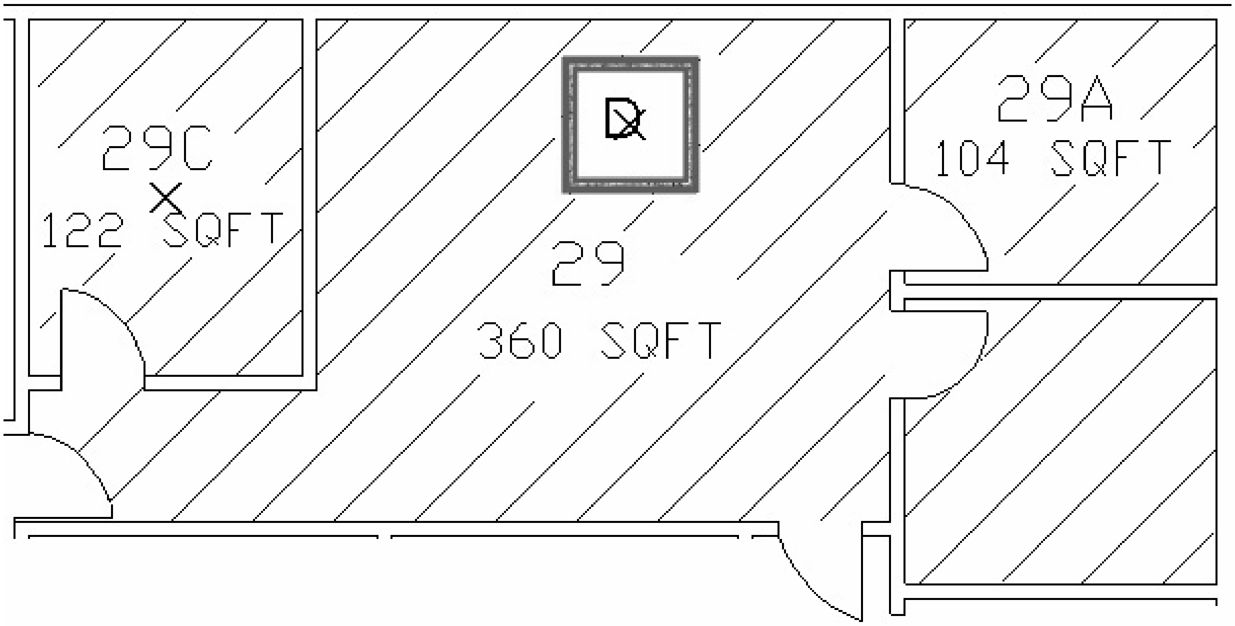

Figure A-3. R-29: Psychophysiology laboratory.

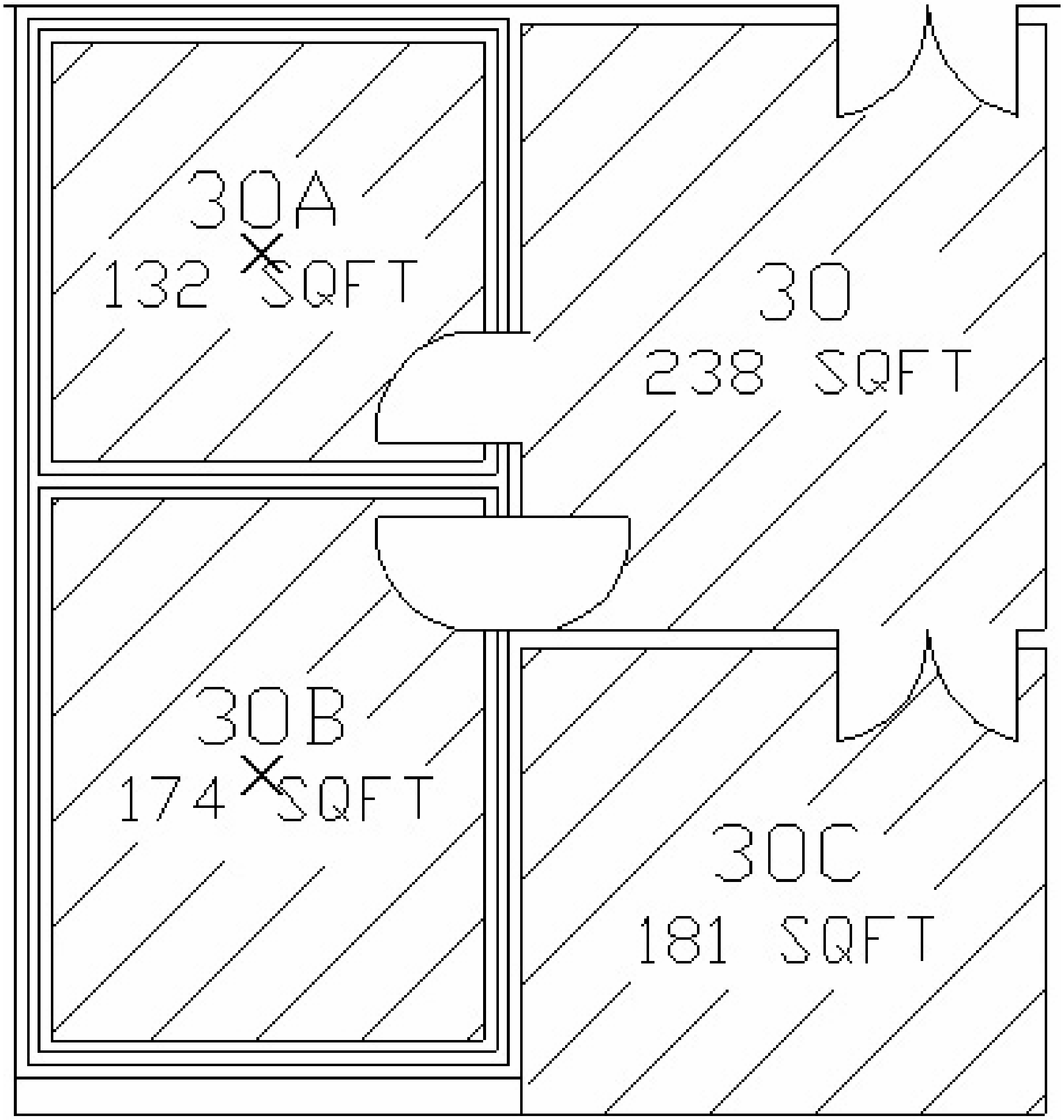

Figure A-4. R-30: Sound perception laboratory.

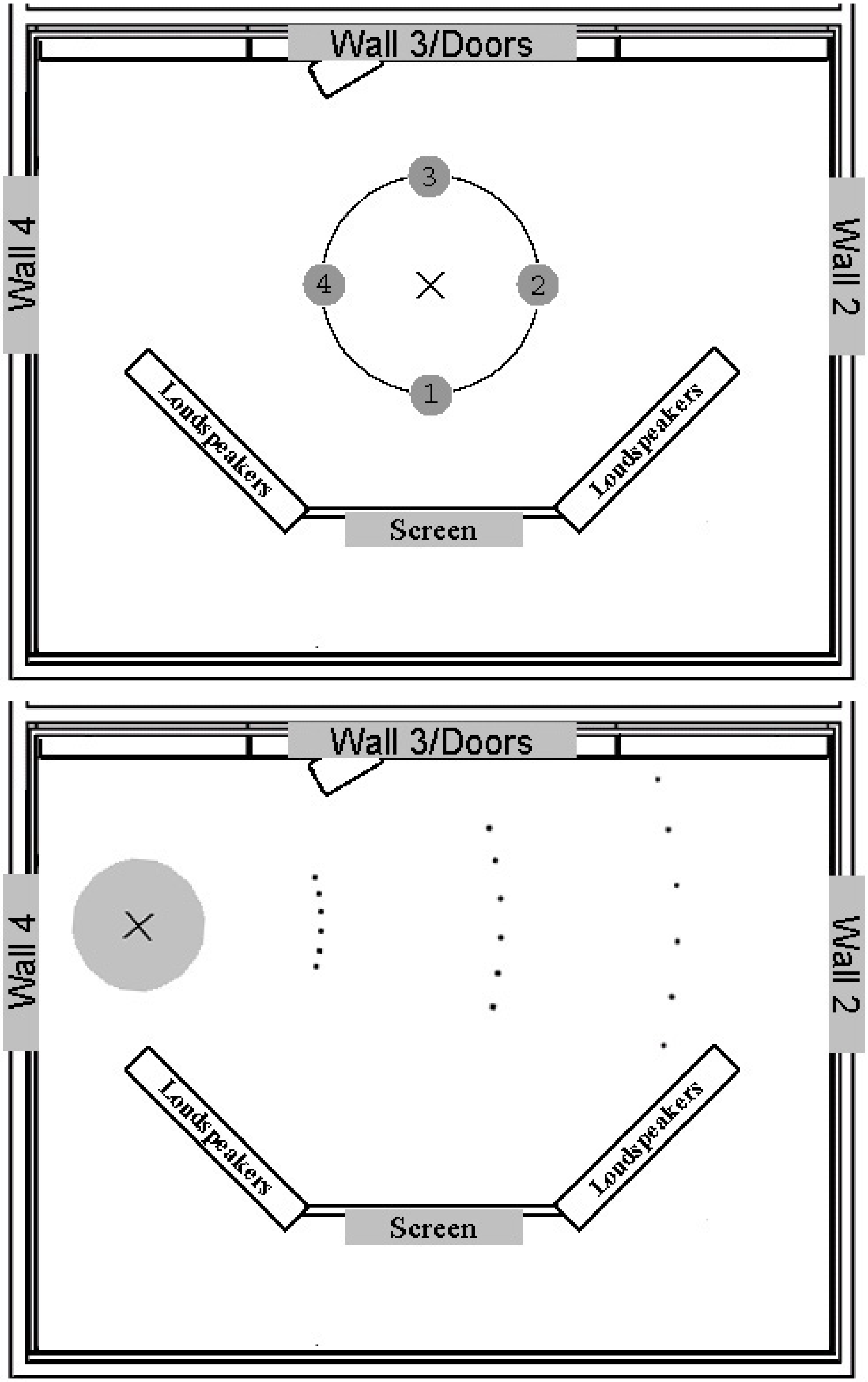

Figure A-5. Hostile environment simulator (HES): chandelier setup and distance setup (2503.6 ft^2).

Appendix B. Choosing and Using a Sound Level Meter

An SLM is an instrument designed to respond to sound in approximately the same way as the human ear and to provide objective measurements of SPL. Sound level meters are commonly either type 1 (precision instruments) or type 2 (general purpose instruments) in respect to the accuracy of the results in specified circumstances. The requirements for both types of SLMs are specified by international and national standards (e.g., ANSI S1.4-1985; ANSI S1.43-1997; IEC 60651-1979; IEC 60804-1985; and IEC 61672-2002). In the past, SLMs were divided into four types (0, 1, 2, and 3), but types 0 and 3 have been integrated into the two other classes. The precision of SLM depends on the frequency of the measured signal. For middle frequencies, it is defined as ±1 dB and ±1.5 dB for types 1 and 2 SLMs, respectively. At low frequencies, the precision can be as low as ±4 dB.

Many different SLMs are available from various manufacturers (Rion[9], Brüel & Kjær, Casella CEL Ltd., Quest Technologies[10], Larson-Davis, etc.), but each SLM includes a microphone, one or more amplification stages, a filter (optional), a signal detector with a display (read-out) unit, and frequency weighting networks to measure the sound level in the same way as humans hear it. A functional schematic diagram of the SLM is shown in figure B-1.

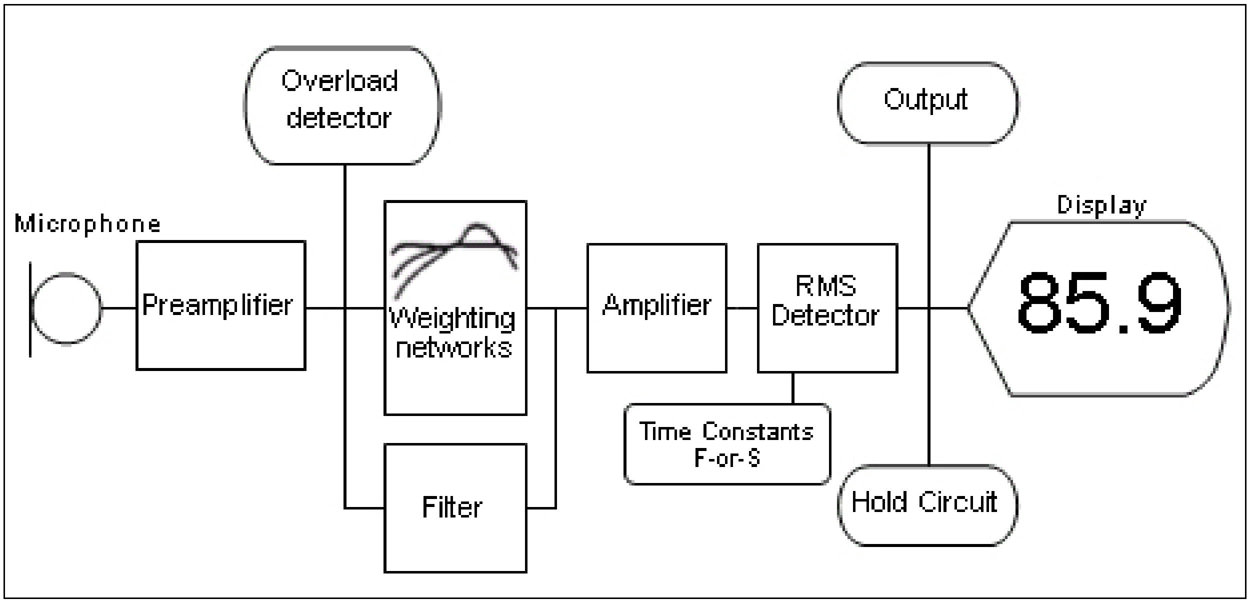

Figure B-1. Functional schematic diagram of the SLM.

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[9] Rion® is a registered trademark of Rion Company Ltd.

[10] Quest® is a registered trademark of Quest Technologies, Inc.

In essence, the selection of an SLM is a selection of requirements for each element shown in figure B-1. Here are some guidelines for making these selections and the use of SLM in general.

Microphone

The correct type and use of the microphone is extremely important in obtaining accurate measurements. Microphones come in many types and sizes. A microphone is typically designed for use in a particular environment and across a specific range of SPLs and frequencies. Two major types of measuring microphones are directional “free-field” (or “gradient”) microphones and omni-directional “diffuse field” (or “pressure”) microphones. The free-field microphones are intended to be used in the free sound field and pointed directly at the sound source. They should not be used in the diffuse field unless they are used with a “random incidence corrector” such as the Brüel & Kjær (B&K) UA0055. Diffuse field microphones are primarily designed to measure sound levels in the diffuse field and in the calibration couplers. If they are used in a free sound field, they need to be held so as to receive the sound source from a “grazing” angle of incidence.

The appropriate microphone size depends on the frequency range and intensities that one intends to measure. Larger microphones are better for low frequency measurements. Smaller microphones are better for high frequency and high intensity level measurements. For example, 1-inch B&K microphones have typical frequency ranges of 1 Hz to 8000 Hz; 0.5-inch microphones range from 5 Hz to 40,000 Hz, and 0.25-inch microphones range from 20 Hz to 100,000 Hz. As microphones increase in size (with respect to the diameter of their membranes), the sensitivity increases and the internal noise level decreases. Larger (1 inch) B&K microphones are more sensitive to sound pressure and can measure SPLs as low as 10 dB, whereas smaller microphones are limited to about 14 dB SPL (0.5 inch) and 35 dB SPL (0.25 inch).

Preamplifier

The input of the SLM is a high gain-matching preamplifier followed by a step attenuator that controls the signal level arriving at signal processing and level detector circuitry. Changing the setting of this attenuator changes the range of the display unit but does not affect the signal-to-noise ratio (SNR) of the measured signal. However, some SLMs have an additional post-processing amplifier to further expand the range of measured values. Changing the volume control of this post-processing amplifier does affect the SNR of the measured quantity.

Weighting Circuits (networks)

The human ear is not equally responsive to all frequencies. It is most sensitive from 2000 to 5000 Hz and to sensitivity changes relative to the sound level. The lower the sound level, the more frequency-dependent is an auditory sensation. Therefore, the responses of the SLM are modified with frequency-weighting networks that represent some responses of the human ear.

These empirically derived networks, such as A, B, and C weighting, approximate the equal loudness curves for specific loudness levels. The A-scale approximates the inverse of the ear's response to low-level sounds (40 phons). This scale is commonly used in measuring noise to evaluate its effect on humans and has been incorporated in many occupational noise standards. The B-scale approximates the inverse of the ear's response at moderate levels (70 phons), and the C-scale approximates the inverse of the ear's response to high sound levels (100 phons). Table B-1 shows the frequency-dependent functions underlining "A," "B," and "C" scales. Sometimes, an additional weighting curve "D" is also used. The D-curve has been designed to match the perceived noise level (annoyance) of high-level industrial and aerodynamic noises. Sound level meters usually have also a linear or "Lin" network. This network does not weight the signal but enables the signal to pass through without modification for measuring the true sound pressure levels.

Table B-1. Relative response of SLM weighting circuits

		Weighted response (dB)	
Octave-center frequency (Hz)	**A scale**	**B scale**	**C scale**
31.5	-39.4	-17.1	-3.0
63	-26.2	-9.3	-0.8
125	-16.1	-4.2	-0.2
250	-8.6	-1.3	0
500	-3.2	-0.3	0
1,000	0	0	0
2,000	1.2	-0.1	-0.2
4,000	1.0	-0.7	-0.8
8,000	-1.1	-2.9	-3.0
16,000	-6.6	-8.4	-8.5

The A, B, and C curves are based on equal loudness curves for pure tones. It soon appeared that with the exception of the A-curve, none of the approximations correlated very well with the perceived loudness of real-world complex sounds. Thus, B and C weightings became only occasionally used. However, the C-weighting is again being used, not because of correlation properties hitherto overlooked, but simply because of its shape. The difference between the SPL measured with A-weighting and C-weighting provides information about the spectral properties of the sound measured.

Filters

The frequency range of the measured sound may be limited at low and high frequencies (band-pass filtered from 20 Hz to 20 kHz) to reduce the effects of vibrations, equipment noise, and inaudible sounds on the results of measurements. In some more expensive SLMs, the frequency range from 20 Hz to 20 kHz can be divided into sections or bands by means of electronic filters that reject all signal frequencies outside the selected band. These bands usually have a bandwidth of either one octave or one-third octave. The process of dividing complex sound into its component frequency bands is termed *frequency analysis*, and the results are presented on a chart called a *spectrogram*.

RMS Detector

A SLM is always equipped with a detector. The purpose of the detector is to convert the measured sound pressure to an SPL and to provide a reading proportional to one of the waveform characteristics. After the input signal has been weighted (filtered) and amplified, it becomes rectified and fed into a signal detector circuitry providing the actual signal for the display. All SLMs are equipped with root mean square (rms) detector circuitry as opposed to peak, VU, or average value detector circuitry used in some other meters.

The rms value is used because it is directly related to the amount of energy in the sound being measured. Type 1 SLMs use “true rms” detectors that provide a true rms reading, regardless of the type and shape of the signal (high crest factor). Type 2 SLMs frequently use a “sine wave-based rms” detector that provides proper readings only for sine waves and similar signals (low crest factor). Therefore, signals with large peak-to-rms ratio (crest factor) may not be measured properly with type 2 SLMs.

Some SLMs include a circuit for measuring the peak value of the impulse sound. This circuit is known as a *Hold Circuit* and it stores either the peak value or the maximum rms value.

Time Constants

Most natural sounds fluctuate in level over time, and their measurement depends on the degree of signal integration provided by the measuring circuitry. Longer integration results in more signal averaging and fewer fluctuations in the displayed level values. The degree of integration is defined by the *time constant* (detector response time) of the detecting circuitry. If the detector input signal changes suddenly, the time constant expresses the time it takes for the detector output signal to reach 63% of its final value.

Two basic detector response times have been standardized: “fast response” (F) and “slow response” (S). Fast response (T= 125 ms) provides a quickly reacting display response that enables the user to follow and measure fluctuating sound levels that are not varying too rapidly. Slow response (T=1 s) provides a greater integration of the highly variable signal and averages the display fluctuations, which would otherwise be impossible to read with the “F” characteristic. Some SLMs also provide a third time constant (T=35 ms) called “impulse response” (I) that is used to measure the SPL of a single impact or impulse sound. To permit a convenient “read-out” of the display, the decay time for impulse response is 1.5 seconds.

Display (read-out unit)

The "read-out" unit displays the sound level in decibels or some other derived unit such as dB(A), which means that the measured sound level has been A-weighted. The display can be either numeric or analog. The decibel scale used in analog displays can be either linear or logarithmic, depending on the meter signal detector circuitry. The measured signal may also be available at output sockets, in either AC or DC form, for connection to external instruments such as level or tape recorders to provide a record and/or for further processing.

Sound Level Range

The typical range of an SLM may be as small as 70 dB (50 to 120 dB SPL) or as large as 150 dB (0 to 150 dB SPL). For determination of compliance with the Hearing Conservation Amendment, the Occupational Safety and Health Association (OSHA) requires that all sound levels from 80 to 130 dB A-wtd be included in noise measurements (OSHA, 2002).

SLM Calibration

SLMs should be calibrated periodically in order to provide precise and accurate results. Placement of a portable acoustic calibrator (IEC 60492-2003; ANSI S1.40-1984), such as a B&K 4230 sound level calibrator (94 dB SPL at 1 kHz) or a B&K 4220 piston phone (114 dB SPL at 250 Hz), directly over the microphone is the best method. It is a good measurement practice to calibrate SLMs immediately before and after each measurement session.

Cost of the Instrument

B&K sets the standard for SLMs and as such, is the most expensive, ranging from $15,000 to 25,000 with accessories. Modestly priced alternatives currently are between $800 and $5,000; the average is about $2,500, depending on the accessories one needs. A fairly reliable Radio Shack[11] Class 2 SLM can be obtained for less than $50. The difference in cost between the models reflects the calibration standard (i.e., class) and durability of the equipment. Type 1 B&K equipment might be expected to last 50 or more years (although the microphones will need to be changed every 20 years). Other companies expect a good 8 to 20 years from their products, while the least expensive ones may last 2 to 5 years.

Measurement Practice

The users should always follow the SLM manufacturer's instructions regarding the type and size of microphone and its orientation toward a sound. Care should be taken to avoid shielding the microphone by persons or objects (ANSI, 2001). The person conducting the measurement should hold the microphone as far from his or her body as is practical (Earshen, 1986). This is especially important in a diffuse sound field. It is also important to hold the SLM away from a

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[11] Radio Shack® is a registered trademark of Tandy Corporation.

person’s body when one is measuring low frequencies because body reflections of frequencies less than 100 Hz can accrue to 6 dB of error. Tripods can be used to avoid the measurement error caused body reflections.

When one is making out-of-doors measurements, it is usually preferable to point the microphone upward (to avoid interference from reflected high frequencies) and as far from the body as is convenient. If winds greater than 10 meters per second are present, a wind screen should be used to minimize the low frequency interference caused by air passing across the microphone. A wind screen will attenuate this wind noise by approximately 20 dB.

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