

Naval Submarine Medical Research Laboratory



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CHARACTERIZING NOISE FIELDS IN SHIPBOARD SPACES

Robert J. Sylvester

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Characterizing noise fields in shipboard spaces

Robert J. Sylvester

Naval Submarine Medical Research Laboratory
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SUMMARY PAGE

THE PROBLEM

The problem involves the establishment of a method for characterizing discrete tone sound fields in reverberant shipboard spaces, in order to assess the noise hazard in these areas and establish criteria for an acceptable noise environment.

THE FINDINGS

Detailed contour sound field maps of a reverberant test chamber insonified with discrete tones were developed. These maps revealed a significant spread (35.2 dB) in sound pressure levels from point to point in the sound field. These results demonstrate that measurements taken with a conventional non-integrating sound level meter could severely underestimate or overestimate the actual noise hazard, depending on the measurement locations chosen. On the other hand, measurements obtained with an integrating sound level meter were comparable with the results of the sound field maps. Personal noise dosimetry was also used, but extraneous noise produced by the subjects affected the results. Therefore, dosimetry was not considered a viable alternative for measurement of noise hazard.

APPLICATION

These findings contribute to the adoption of a method for characterizing discrete tone sound fields in ships' spaces.

ADMINISTRATIVE INFORMATION

This research was carried out under a task plan entitled, "Development of acoustic habitability standards for ships' spaces subjected to intense tones," and was funded by Program Executive Office Surface Ship ASW Systems Task No. SSAS-91-77A01R2 dated 14 December 1990, "AN/SQY-1 Frequency Array Testing," Naval Sea Systems Command PMO 424. The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 29 April 1993, and designated as NSMRL Report 1185.

ABSTRACT

Three methods of characterizing discrete tone sound fields were tested in a reverberant compartment. Method one uses sound field mapping, method two implements an integrating sound level meter, and method three uses personal noise dosimetry. Sound field mapping resulted in a detailed and accurate visual representation of the sound field, but because the procedure is both complicated and time consuming it is not appropriate for day-to-day analysis of compartments. The dosimetry measurements were erratic and did not compare well with the sound field mapping measurements. The dosimeters were influenced by the extraneous noise produced by the activities of the test subjects wearing the dosimeters. Consequently, personal noise dosimetry cannot be considered a reliable method for characterizing sound fields for the conditions of this test. An integrating sound level meter combines the accuracy of the sound field maps with the simplicity of operation of the personal noise dosimeters. A single number was attainable that was representative of the noise hazard associated with discrete tones in reverberant compartments.

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Characterizing Noise Fields in Shipboard Spaces

Introduction

Shipboard personnel are exposed daily to intense noise from various sources. The amount of the noise exposure depends on various conditions, including the characteristics of ship's spaces. The spaces of current concern are the ship's berthing areas, which may vary from highly absorptive to highly reverberant. We consider here only thoroughly reverberant spaces. Sound levels in reverberant spaces vary substantially with time and measurement location. The severity of the variation in sound level depends on the amount and position of reflective and absorptive materials, as well as their effective roughness, porosity, flexibility, and in some cases their resonant properties. Parallel surfaces (ceiling, floor, and walls) actually enhance standing waves by minimizing the distance between reflections. Even the positioning of furniture and people cause the sound field to vary, making it difficult to characterize it.

Assessing the noise exposure in these areas, and establishing criteria for an acceptable noise environment, demand the adoption of a method for characterizing the noise level. This method should provide a numerical evaluation of the noise (preferably in terms of a single number) that will bear a meaningful relation to the amount of interference caused by the noise. In order to determine the potentially adverse effects of noise on shipboard personnel, three methods of characterizing the sound field for discrete tones in reverberant spaces were tested. Method one uses sound field mapping, method two implements a hand held integrating sound level meter, and the third method uses personal noise dosimeters.

When dealing with discrete tones (a sound wave that is a simple sinusoidal function of time) the main concern is standing waves. Standing waves result from reflections caused by the walls, floor, ceiling, and other surfaces in an enclosed compartment. Standing waves can be described as the combination of an outward-traveling wave and a backward-traveling wave. The outward-traveling wave is the original free-field wave that started out from the source, and the backward-traveling waves are the reflections that are making their second, third, fourth, and so on, round trips. The addition of these outward and backward-traveling waves in some places, and cancellation in others, cause distinct patterns of sound pressure level; maxima in some places, minima in others (Harris,1991; Hassall, Zaveri,1988).

Broad-band noise may be considered to be comprised of many frequency components. Each frequency component exhibits a particular standing wave pattern that may be measured using suitable narrow-band analysis. However, with broad-band analysis, a summing effect takes place across the spectrum so that the difference between sound pressure maxima and minima is reduced substantially. With continuous broad-band noise having no pronounced discrete frequency components, useful analyses of ships' spaces can be made using simple sound level meters. When dealing with intermittent discrete tones, as is our present concern, the averaging effect is minimal and a great variation in sound level can occur throughout the compartment. This effect is worsened when working in highly reverberant compartments. In such situations, simple sound level meters produce exceeding-

ly erratic estimates of the auditory hazard of tones.

Method

Exposure chamber and noise stimulus.

Experiments were conducted on the effects of 24-hour exposures to pure tones on Navy personnel. The measurements reported below were taken from these habitability experiments to establish exposure levels.

A schematic of the testing chamber used for the measurements is shown in Figure 1. Six beds occupied two thirds of the chamber, and three tables were located in the areas indi-

cated. Figure 2 shows a photograph of the berthing area and the location of the speakers. Twenty Owi-202 speakers were evenly spaced around the perimeter of the room at a height of 2.4 m to center, and two coaxial speakers in infinite baffles occupied opposite corners of the room to simulate shipboard noise by enhancing the lower frequencies. Each speaker was driven by a separate amplifier. The amplifier outputs were adjusted to produce a uniform near-field sound pressure level from each of the individual speakers.

The stimuli were generated by a Hewlett Packard 325A universal source generator

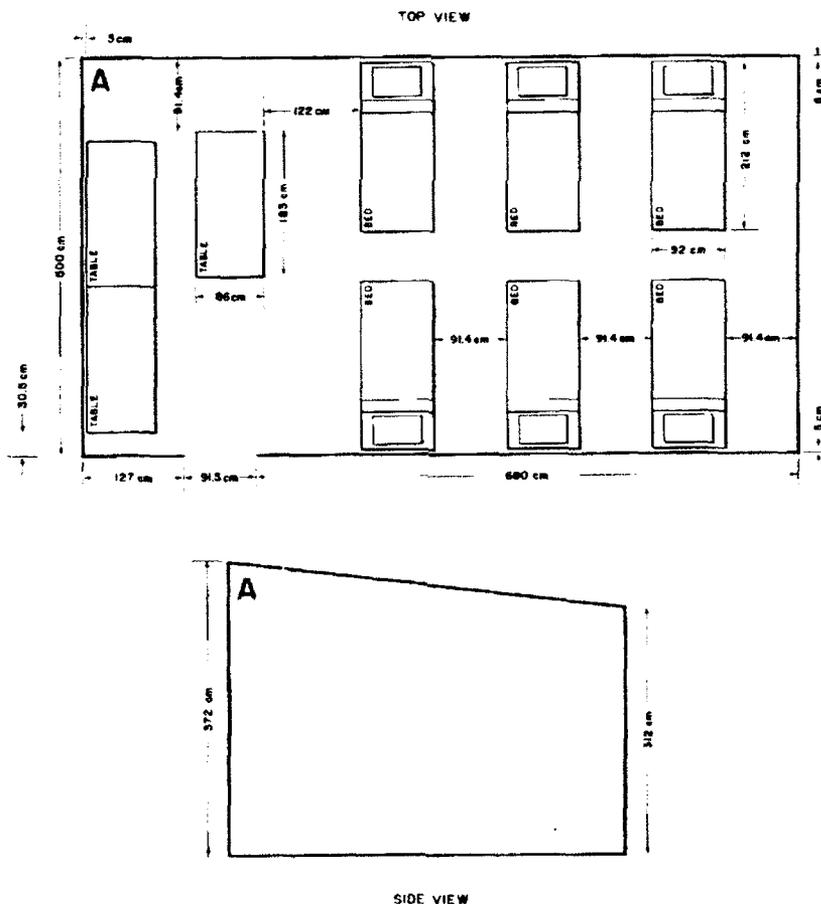


Figure 1. Schematic of exposure chamber: Top View and Side View

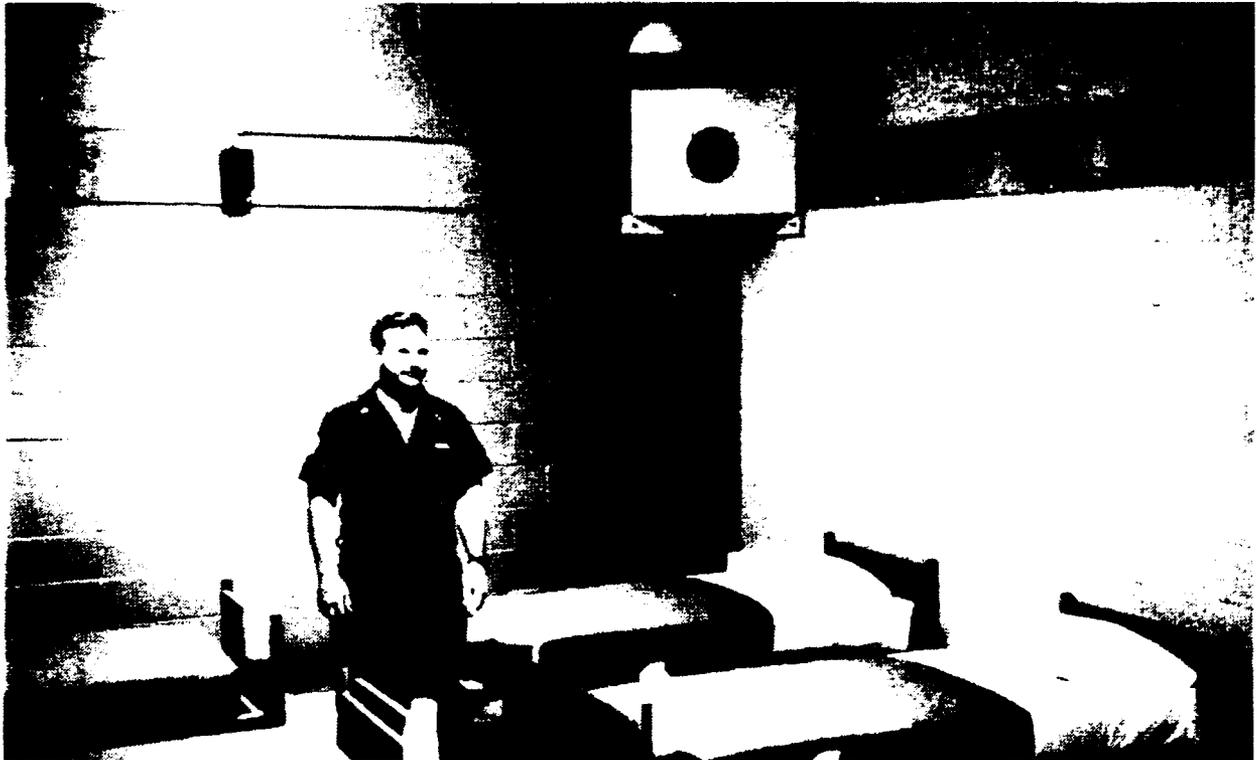


Figure 2. Exposure chamber.

controlled by a computer. The signal from the generator was fed through a Rockland 751A programmable elliptic filter and Crown D-75 amplifiers before reaching the 20 Owi-202 speakers.

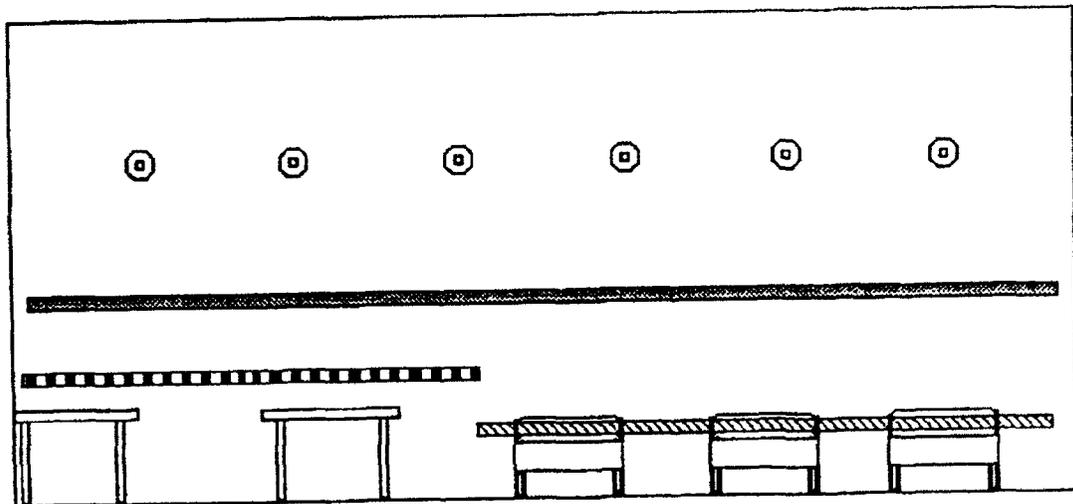
For the habitability experiments, the stimuli consisted of six discrete tones (720, 800, 880, 960, 1040, 1120 Hz) presented at the same amplitude. Each tone was presented for a duration of 1 s with 50 ms rise and fall times to eliminate transients. The tones were presented in pseudorandom sets of six contiguous tones. The six tone sets were repeated every 23 s (20% duty cycle). The six permutations were continuously cycled through for an exposure period of 24 hrs.

Sound Field Mapping. Sound field maps were generated for three horizontal planes in the exposure area (Figure 3). The three heights used

were standing, sitting, and sleeping, at ear level for an average male (5'9"). All measurements were recorded on a Bruel & Kjaer (B&K) type 2133 real-time spectrum analyzer.

The map generated for the horizontal plane at standing height encompassed the entire room (Figure 3). The measurements were taken at regularly spaced points within the room using a predefined grid (80 cm X 80 cm). A more detailed map was generated for the map at the sitting level, which used a 30 cm X 50 cm grid in order to find the absolute maximum and minimum sound pressure levels produced by the standing wave patterns. The third map (sleeping level) used a 60 cm X 100 cm grid.

A map was generated for each tone (720, 800, 880, 960, 1040, and 1120 Hz), as well as a



STANDING LEVEL: [FIG. 5]
 SITTING LEVEL : [FIG. 6]
 SLEEPING LEVEL: [FIG. 7]

Figure 3. Each level depicts the location of a horizontal plane. The sound field maps shown in figures 5, 6, and 7 were generated from measurements taken in each of the three planes above. The map corresponding to each level is indicated in brackets.

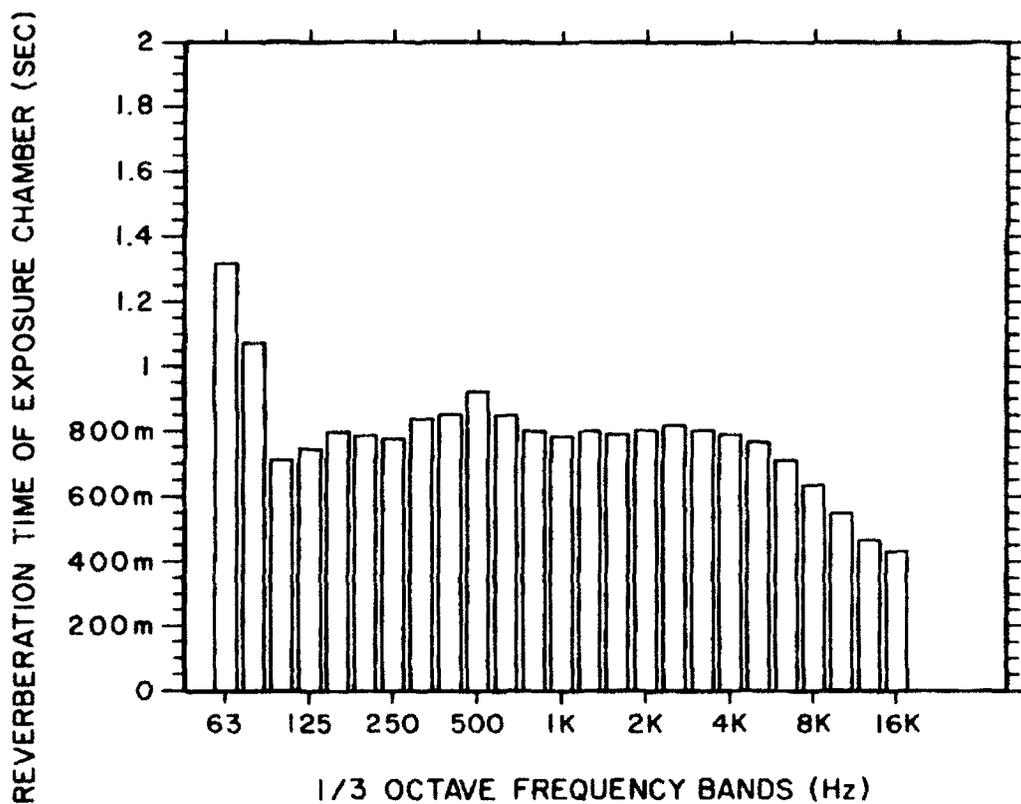


Figure 4. Reverberation times of exposure chamber (1/3-octave bands).

frequency sweep from 720-1120 Hz. The stimuli were generated in the same manner as described above for the testing of subjects. Each measurement was stored using the B&K type 2133 spectrum analyzer with third octave analysis, linear averaging, and A-weighting. To obtain an accurate reading for each frequency, each tone was presented for 4 s rather than the 1-s pulse used for testing subjects. A 2-s sample was taken, programmed to trigger after a 1-s delay. The 1-s delay allowed the sound level in the room to reach a steady state. The measurement data were transferred from the input memory to the buffer memory. After the 4-s tone, a 1-s delay allowed for complete decay of the noise before the next tone was presented. Reverberation measurements of the chamber show that 1 s is sufficient time for the noise level to reach its ambient level. It can be seen from Figure 4 (1/3 octave reverberation times of the exposure chamber) that the reverberation time for the frequencies of concern is approximately 800 ms. A total of 2233 measurements were taken for 319 different locations in the sound field.

The measurements taken for the frequency sweep were 30 s in duration. The frequency sweep (720 - 1120 Hz) was 10 s in duration. The analyzer was programmed to trigger after 1 s. Unlike the discrete tones, the signal was continually fluctuating and a steady state condition was not produced, but the delay was necessary to eliminate transients from the speakers and to allow the sound field to saturate before the instrument began sampling. Another 1-s delay after the noise source was turned off allowed the signal to decay before another measurement was taken.

The data stored in the buffer of the B&K 2133 were transferred to a IBM Personal Computer and converted into ASCII code. A

B&K mapping program (CPLOT) was used to linearly interpolate between each measurement point. The results were presented in the form of contour maps depicting the sound pressure levels throughout the compartment in a specified horizontal plane (Figures 5, 6, 7).

Hand held Sound Level Meter. In this measurement situation, the widely fluctuating display of a traditional non-integrating sound level meter makes it extremely difficult to determine the correct sound level. Therefore, an integrating sound level meter was used. These instruments summate noise energy on a relatively long term basis and divide the value obtained by the elapsed time, thus, providing an equivalent sound pressure level (L_{eq}). In addition, the meter stores the maximum and minimum SPL recorded during the measurement time.

L_{eq} , which is equivalent to L_{av} , is the sound pressure level averaged over the measurement period. It can be considered as the continuous steady sound pressure level which would have the same total acoustic energy as the real fluctuating noise over the same time period. Thus, the L_{eq} is in fact the RMS sound level with the measurement duration used as the averaging time.

L_{eq} is given as:

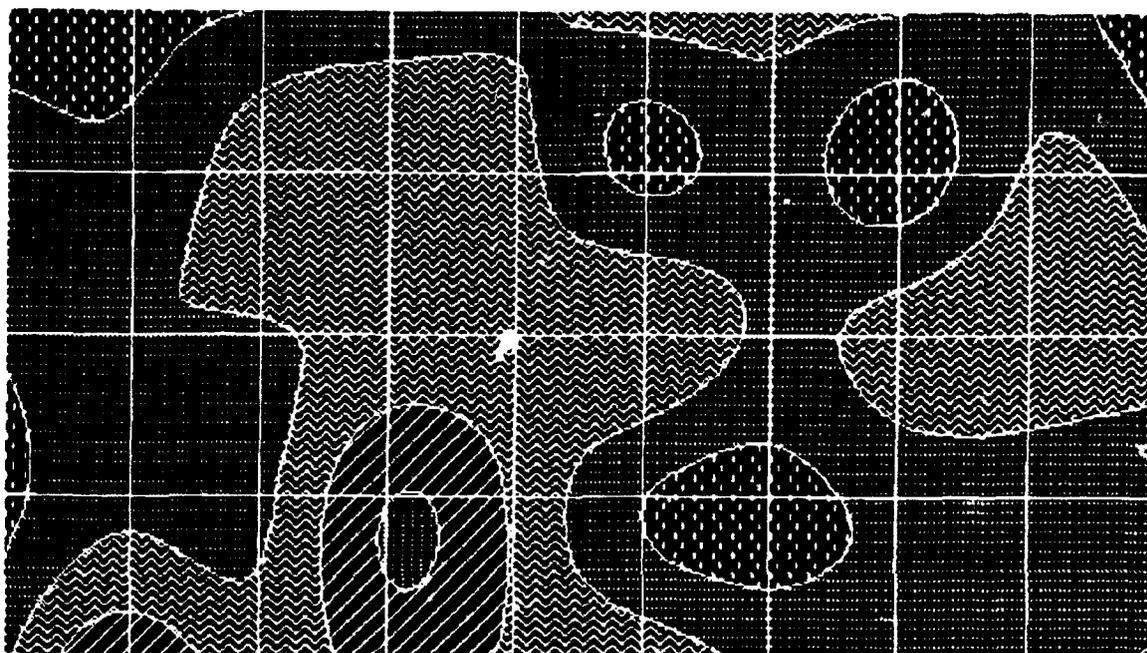
$$L_{eq} = L_{av} = 10 \log \left(\frac{1}{T} \int_0^T \frac{p^2(t)}{p_0^2} dt \right)$$

T = measurement duration.

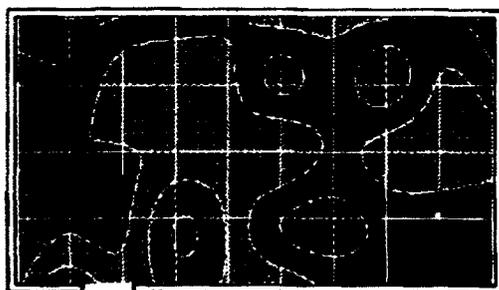
$p(t)$ = sound pressure.

p_0 = reference sound pressure of 20 μ Pa.

This method was implemented with the B&K 2230 Sound Level Meter (SLM) with a B&K



EXPOSURE CHAMBER



LOCATION OF MAP

■	79.2 - 80.0
▨	80.0 - 80.7
▩	80.7 - 81.5
■	81.5 - 82.2
■	82.2 - 83.0

Figure 5. Sound pressure contour map of the reverberation chamber. Elevation: 162 cm (standing level), $L_{eq} = 82.9$ dB, Stimulus: 720-1120 Hz sweep.

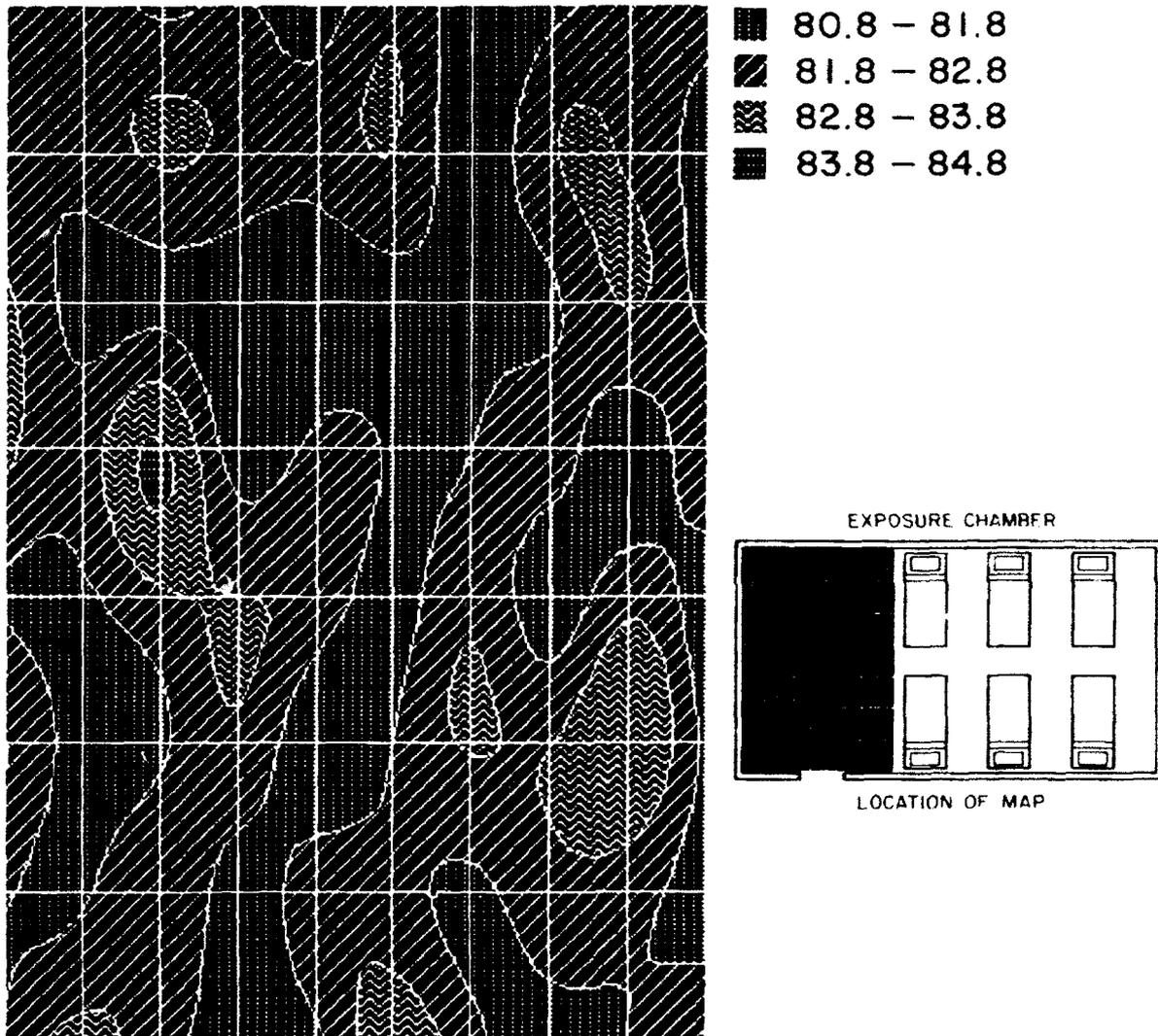
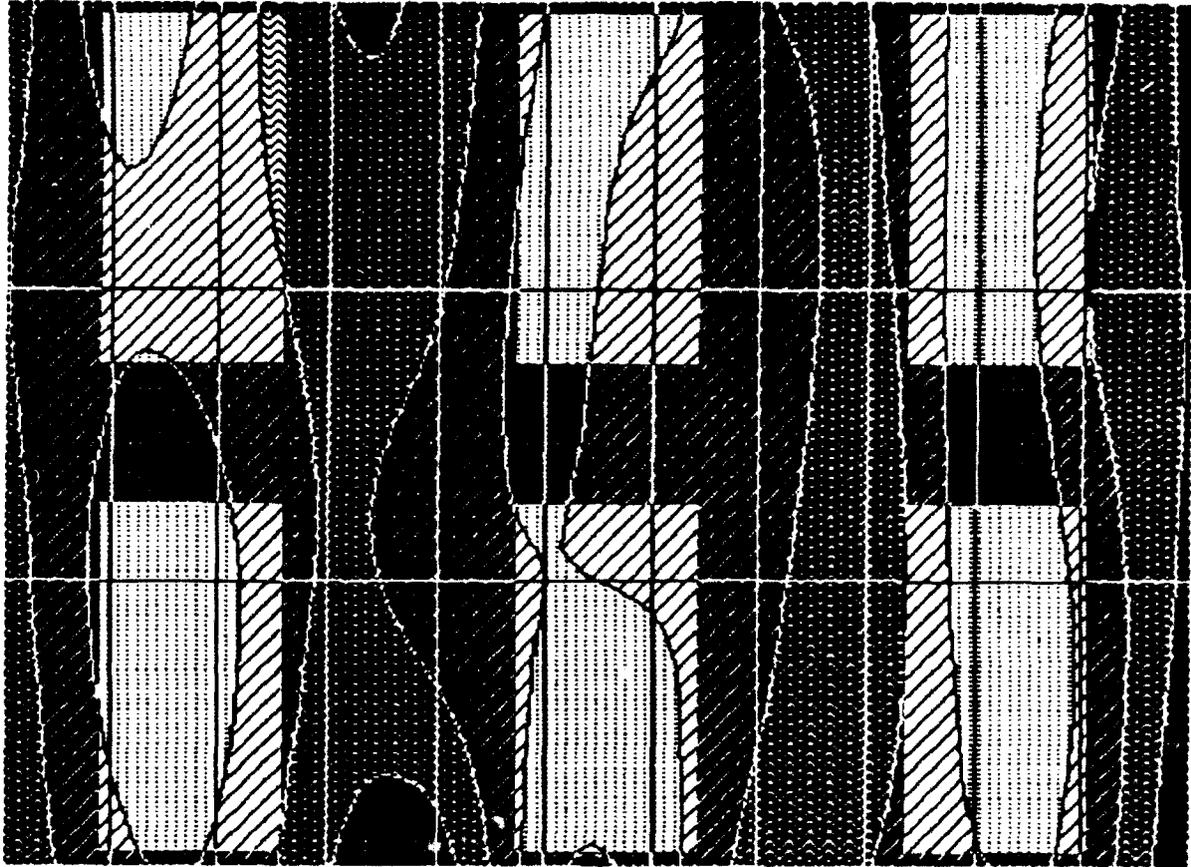
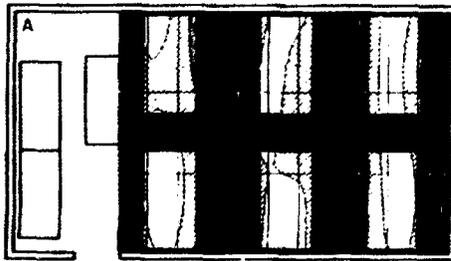


Figure 6. Sound pressure contour map of the reverberation chamber. Elevation: 125 cm (sitting level), $L_{eq} = 82.1$ dB, Stimulus: 720-1120 Hz sweep.



EXPOSURE CHAMBER



LOCATION OF MAP

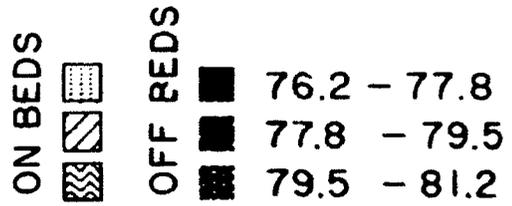


Figure 7. Sound pressure contour map of the reverberation chamber. Elevation: 60 cm (sleeping level), $L_{eq} = 79.1$ db, Stimulus: 720-1120 Hz sweep.

1625 third octave filter to analyze the exposure area. A spatial temporal measurement was obtained by performing a 1/3-octave frequency analysis with A-weighting while moving the SLM uniformly throughout the compartment. The measurement length was 45 min, and was repeated three times to obtain a L_{eq} representative of the actual noise dose a subject would receive in that environment. The noise stimulus for these measurements was similar to the discrete tone sequences described for the habitability experiment. The only difference was that the 23-s delay between sequences was omitted. Therefore, the stimulus was present continuously (100% duty cycle).

The SLM simultaneously carries out the following measurements: sound pressure level (SPL), Maximum SPL, Minimum SPL, and L_{eq} . Obtaining the L_{eq} , min, and max measurements were of most importance because they are directly comparable with a statistical analysis of the samples taken with the real-time frequency analyzer (B&K type 2133) with Sound Field Mapping.

Personal dosimeter readings. Eight 24-hr exposures were performed in the experiment. Each group was comprised of six subjects, who were allowed to move freely about the exposure room. Each subject wore a db-3100 Metrosonics dosimeter (a device that measures the actual noise dose received by a subject by measuring the sound pressure level as a function of time). The dosimeters were clipped to the subjects belts and the microphones were clipped to their shirt collars approximately 10 cm from the ear.

The results can be displayed as a time history of the noise dose on a graph as in Figure 8, or as an equivalent sound pressure level such as L_{eq} . Two minutes were required to read the data into the computer and reprogram

the dosimeters. Only eight min of data were lost during data storage and reprogramming in a 24-hr period.

Each dosimeter was programmed for two 6-hr run times during the day, and a 12-hr run time during the night. A shorter run time allows time history statistics to be saved more frequently. The dosimeters were configured using an A-weighting filter.

In addition to the personal dosimeters, two control dosimeters were placed in fixed positions in the exposure room during each 24-hr exposure. The locations were never the same for any two exposures, resulting in a total of 16 different measurement locations. The control dosimeters were programmed with the same format as the personal dosimeters.

RESULTS

Sound Field Mapping. The data generated using method one (Sound field mapping), with discrete tones showed a significant spread in sound pressure levels (SPL) from point to point. The maximum SPL was 92.7 dB and the minimum was 57.5 dB. This wide range of SPL values demonstrates the significant effect standing waves have in reverberant compartments. A power average across all frequencies and measurement locations was calculated on these same data, resulting in an average SPL (or L_{eq}) of 82.7 dB.

Three maps were generated using the measurements obtained with the frequency sweep for three different planes. The map generated at 162 cm (standing level) resulted in a power average of 82.9 dB with a standard deviation across 50 different locations of 0.6 dB (Figure 5). The map generated at 125 cm (sitting level) resulted in a power average of 82.1 dB with a standard deviation across 139 dif-

ferent locations of 0.7 dB (Figure 6), and for 60 cm (sleeping level) the power average was 79.5 dB with a deviation across 48 different locations of 1.6 dB (Figure 7).

The results for the sleeping level show a 2 dB drop in SPL, and a higher deviation when

compared with the data from the other two planes. Figure 7 demonstrates how the absorptive qualities of the bedding materials attenuate the SPL in the areas closest to the beds. The SPL dropped 3.0 dB above the beds (depicted with white blocks on the contour map (Figure 7)). This attenuation caused

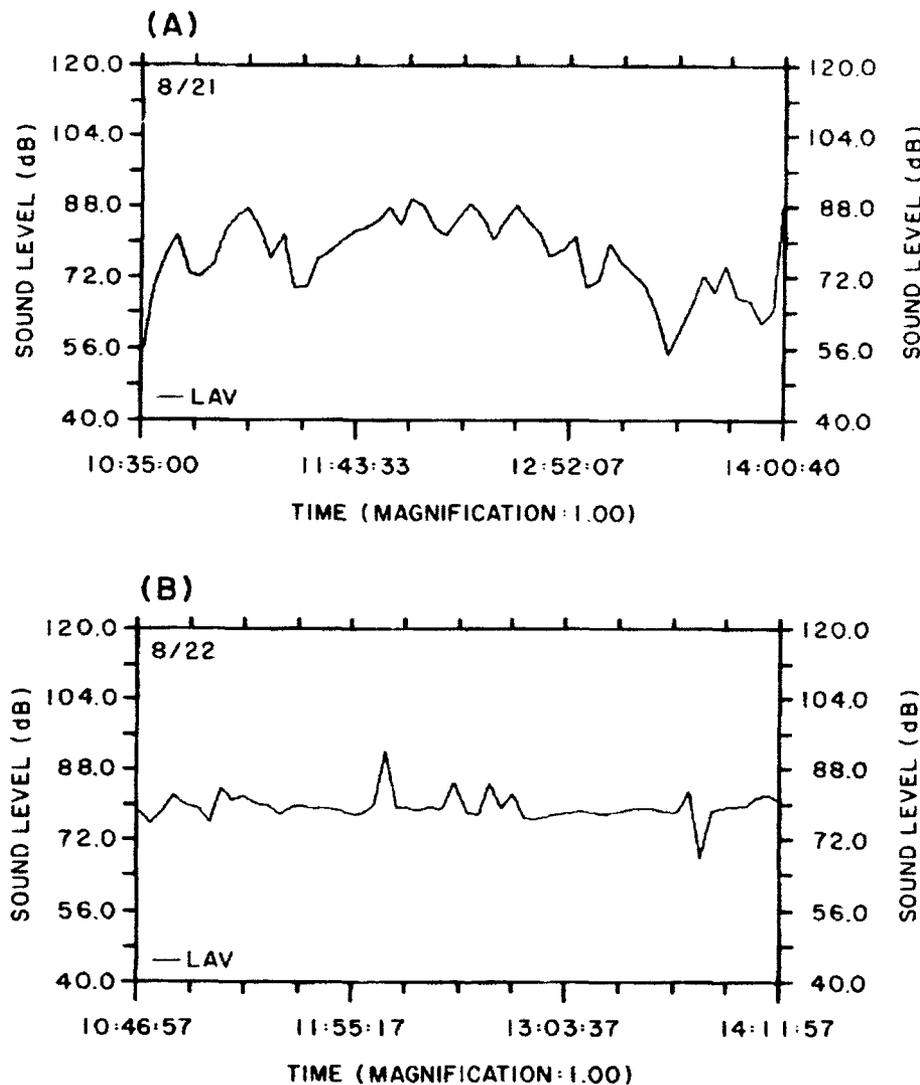


Figure 8. (A) Dosimeter data showing the sound pressure levels vs. time. The levels were generated by the subjects' activity and background noise. (B) Sound pressure levels were generated from a combination of the tone. Stimuli ($L_{eq} = 83$ dB) and the subjects' activity. Noise stimuli present 20% of the time (20% duty cycle); 7 dB must be added to the results above for comparison with SLM and mapping data (100% duty cycle).

the increased variation in levels above and around the beds, which accounts for the higher deviation of 1.6 dB at the sleeping level.

Hand held Sound Level Meter. The three 45-min continuous measurements taken with the integrating sound level meter, resulted in L_{eq} 's of 82.8, 82.9, and 83.2 dB. The mean of these data is 83.0 dB and the standard deviation is 0.17 dB. Comparing the mean with the power average of all the data generated for the sound field mapping resulted in a difference of only 0.34 dB.

Personal dosimeter readings. Personal dosimeter data was collected during the habitability experiment described earlier, during which the stimulus was present 20% of the time (20% duty cycle). Therefore, the dosimeter results reported below are adjusted by +7 dB for comparison with the sound field mapping and integrating SLM results obtained when the stimulus was present 100% of the time (100% duty cycle).

Personal dosimeter data resulted in 6-hr L_{eq} readings ranging from 91.6 dB to 99.5 dB, and the control dosimeter data resulted in 12-hr L_{eq} measurements ranging from 88.3 dB to 95.6 dB. Figure 8a shows the dosimeter data for a period during which the noise stimuli were not present. Figure 8b shows dosimeter data from the same subject on a separate occasion. During this dosimeter reading, noise stimuli were present at an L_{eq} of 83 dB (determined by a B&K 2133 integrating SLM). Therefore, the sound pressure level readings in Figure 8a represent the noise generated by the subjects' activity and contributions from background noise, and the readings in Figure 8b represent the noise generated by the subjects and the tone stimuli.

In comparing graphs 8a and 8b, it is difficult to determine which one was generated during the exposure period. This implies that the subjects were generating random noise at a level equal to or greater than an L_{eq} of 90 dB during the 3.5-hr period. In addition to extraneous background noise, is the possibility for the subjects to obstruct the dosimeters microphones. The result of such an occurrence can be observed in Figure 8a near 1330.

On the other hand, the results of the control dosimeters compared more closely with the results obtained with methods one and two. Figure 9 shows four hours of dosimeter data from a control dosimeter on the same 83 dB exposure day.

It is evident from the graph that the sound pressure levels were more stable with this measurement. The spikes are decreased in amplitude as well as in number when compared to the subject dosimeter data. Furthermore, the average level (L_{eq}) was 83.6 dB.

Even though the results of the control dosimeter in Figure 9 appears to yield an accurate measurement, L_{eq} results from the other 15 control dosimeter measurements ranged from 88.3 dB to 95.6 dB. This wide range in values was dependent on the location of the dosimeters during the eight exposures. Because the dosimeter microphone remained in the same location throughout the measurement time, it is not as accurate as the temporal-spatial measurements obtained with the integrating SLM.

Discussion

Method one (sound field mapping) demonstrates the difficulties in characterizing the sound field in reverberant compartments when dealing with discrete tones. The 2233

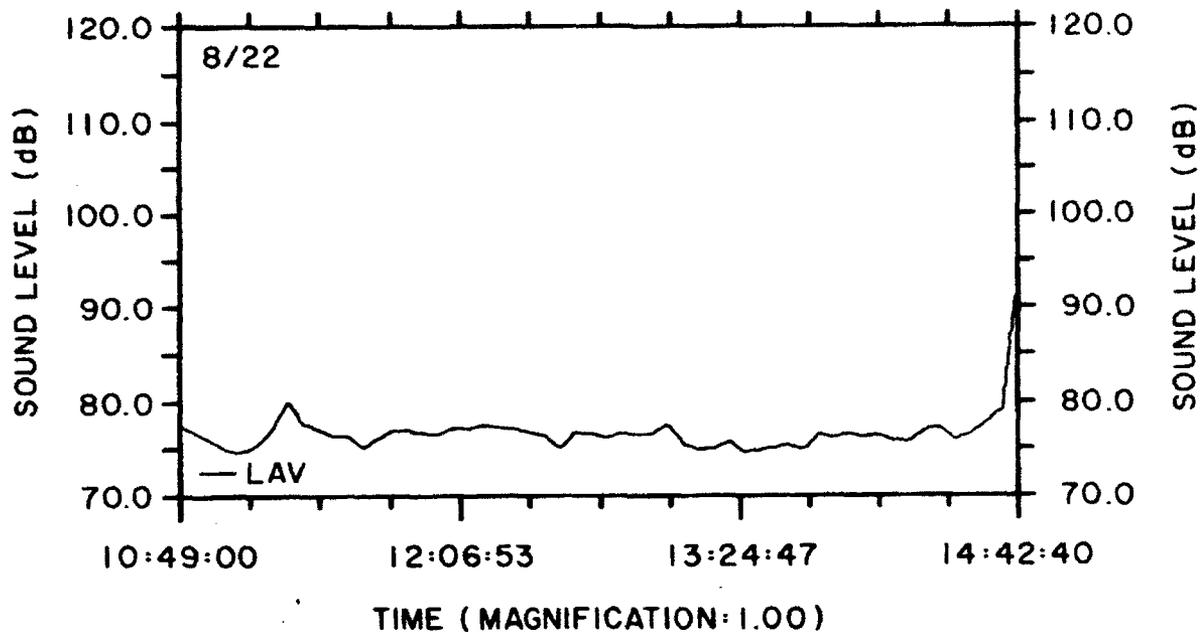


Figure 9. Control dosimeter data for a four hour period, during which the tone stimuli was present at a SPL of 83 dB.

samples recorded show a 35.2 dB spread in sound pressure levels throughout the chamber. This result demonstrates the impracticability of describing the noise hazard in this type of environment. If only a few data points were used, the results could grossly misrepresent the noise hazard. It would be impossible to characterize the noise field, and the noise hazard, by taking only a few random measurements.

The sound field maps in Figures 5, 6 and 7 give accurate and detailed results, but because this method is time consuming, requires expensive equipment, and requires relatively complicated procedures, it cannot be considered an appropriate method for day-to-day analysis of compartments. On the other hand, the results of sound field maps can be used to judge the accuracy of other methods available. One such method available is imple-

mented with an integrating SLM. An integrating SLM is less expensive and much simpler to operate than a real-time analyzer. Additionally, the results of this experiment show the L_{eq} readings taken with the SLM (B&K type 2230) compare well with the power average obtained from the sound field mapping data.

Results from the personal dosimeters were significantly different from the levels obtained with Sound Field Mapping and an Integrating SLM. The measurements of sound exposure were influenced by the subjects' movements and speech.

The scraping of the microphone against materials created extraneous noise, causing the dosimeters to record artificially high levels. These effects were caused by the subjects behavior and by the location of the microphone. Therefore, the circumstances of

this particular experiment resulted in a high degree of variability in personal dosimeter data. This is demonstrated by the dosimeter results in Figures 8a and 8b. The data recorded on a dosimeter during a non-exposure day is shown in Figure 8a, and data recorded during an 83 dB exposure day is shown in Figure 8b.

The mean of the data recorded on the non-exposure day was actually slightly higher than the mean of the data recorded on the exposure day. These results indicate that dosimeters cannot be considered a reliable method for characterizing sound fields in reverberant compartments at sound pressure levels of 83 dB or lower. At higher sound pressure levels the extraneous noise produced by human activity would have a lessened effect, and the data recorded on dosimeters would be more meaningful.

The results obtained with the integrating SLM not only compared well with the sound field maps, but its simplicity of operation, and relatively low cost, make it an attractive alternative to sound field mapping. Even though an integrating SLM is simple to operate, it is important that the particular measurement situation be carefully examined before measurements are taken. The location and type of sound source, as well as the objects and materials located in the compartment will determine how to obtain a uniform measurement.

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