

# SENIOR THESIS

Noise exposure associated  
with marching and pep bands:  
measurements, assessment of risks,  
and possible solutions

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## **ABSTRACT**

High school and college marching bands routinely rehearse and perform in a number of locations, including band rooms, auditoriums, practice fields, and football stadiums. Each of these common locations, as well as others unique to specific ensembles, provides varying risk of hearing loss.

A Larson Davis System 824 Precision Sound Level Meter and Real Time Analyzer was used to record A-weighted sound pressure levels while bands rehearsed and performed. At all times during measurements the researcher wore ER-25 flat response musician's earplugs. The microphone of the System 824 was either placed on a tripod or affixed to an extension, depending on whether the measurement was inside or outside, moving or stationary; the goal in all cases was to place the microphone as close to the subjects' ears as possible without interfering with their duties as band members. The researcher marched extensively with the bands to gather data in a realistic environment.

Using NIOSH recommendations for safe occupational exposure, data are presented according to whether they present no risk for the duration of the measurement or the estimated exposure time, risk for the estimated exposure time but not the duration of the measurement, or risk for both the duration of the measurement and the estimated exposure time. Specific locations in the bands as well as different situations (indoor and outdoor rehearsals and performances, drums only, rehearsals without the drumline, etc.) are analyzed. In addition, an acoustical analysis of a rehearsal hall demonstrates that acoustical modifications to the room would be unsuccessful in reducing exposure levels.

Resulting data indicate a significant risk of short- and long-term hearing loss as a result of rehearsing and performing with marching bands. Exposures that would be considered illegal in the workplace are accepted as commonplace in educational environments. Students and band directors must take steps to recognize the risk posed by various instruments and various locations on the field, and must implement hearing conservation efforts.

## **AN INTRODUCTION TO MARCHING BANDS**

The contemporary marching band originates from battlefield drums and bugles used in eighteenth and nineteenth century military conflicts. Previously intended to communicate

information (march, retreat, go to sleep, etc.), marching bands now exist solely for the purpose of musical entertainment. A modern marching band consists of woodwinds (flute, clarinet, saxophone), brass (trumpet, trombone, mellophone, baritone, tuba; low brass includes all brass except for the trumpet), marching percussion (snare drum, tenors, bass drum, cymbals), and pit percussion (xylophone, vibraphone, suspended cymbals, bongos, tambourine etc.; i.e. anything that cannot be marched on a field).

Marching bands also act as pep bands at football and basketball games, remaining stationary and playing music to excite the crowd. Sometimes a drumset is played in a pep band in place of marching percussion instruments.

Today marching bands are easily recognizable from their performances at the Macy's Thanksgiving Day Parade, their appearances on ESPN commercials (i.e. Ohio State and Michigan), feature films such as *Drumline*, and infamous incidents such as the 1982 California–Stanford game where the Stanford band was caught on the field during the final play and a particularly unfortunate trombone player was run over by a California ball carrier. Beyond the high-profile appearances for a select few, thousands of high school and college bands rehearse and perform throughout the football season on a daily or weekly basis.

A marching band typically performs during halftime at football games, with each member marching to a set of precise locations, called drill spots, on the football field. One set of simultaneous spots on the field for each band member is called a drill set, and a full-length halftime show (usually seven to ten minutes in duration) contains anywhere from fifteen to forty-five sets (also called pages of drill, because drill for a halftime show is distributed in a packet of full-page drill diagrams).

Below is a typical page of drill; it is drawn with the home sideline at the bottom of the page. The yard lines found on a football fields are clearly labeled, as are the home and visitor hash marks (each 17.5 yards from the sidelines in high school football); the end zones are excluded. Each grid box on the drill chart represents 2.5 yards, or 4 standardized marching band steps; a standardized step is 22.5", and is called an "8-to-5" step because 8 steps of the correct size will move a band member 5 yards. Individual band members are labeled with specific letter/number combinations, and to learn their drill they learn the position of their numbers as fixed distances from yard lines, sidelines, and hash marks, and as positions relative to other band members. Other information found on a page of drill includes the page number in that set of drill

(the chart below is the 12<sup>th</sup> page in a set), measure numbers, counts for moves and halts, and other specific instructions.

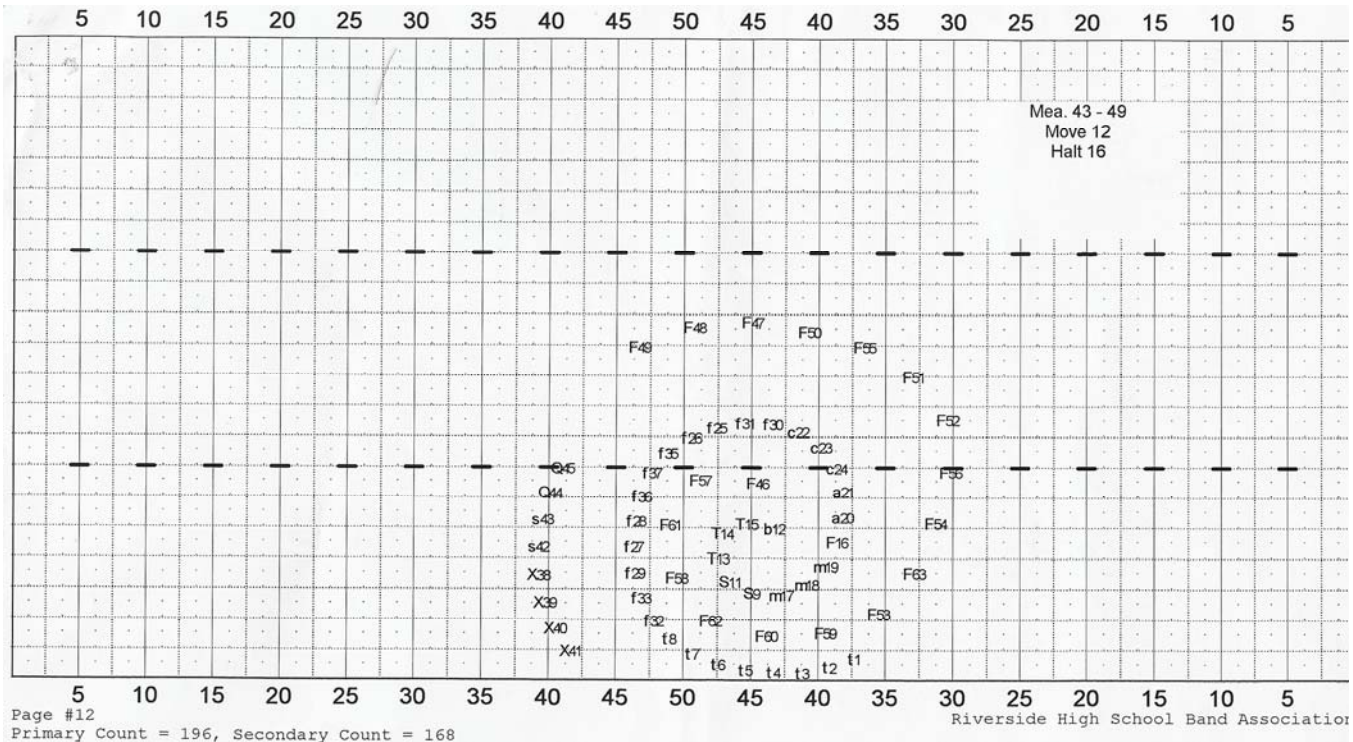


Figure 1: A typical drill chart.<sup>1</sup>

## ACOUSTICAL TERMINOLOGY

### Sound Pressure Level

Humans judge the relative loudness of two sounds by the ratio of their intensities. As a result, and because audible sound intensities range from approximately  $10^{-12} \text{ W/m}^2$  to  $10 \text{ W/m}^2$ , it is appropriate to use a logarithmic scale to express these quantities. The most commonly used scale is called the decibel scale. Decibels (dB) are expressed in reference to a specified value. For sounds transmitted through air, this reference intensity is  $10^{-12} \text{ W/m}^2$ , the approximate intensity of a 1000 Hz tone that is barely audible to someone with completely unimpaired hearing<sup>2</sup> (i.e. an adolescent female). Sound pressure level (SPL) “is a measure of the amplitude of the pressure change that produces the sound. This amplitude is perceived by the listener as loudness”<sup>3</sup>. For sound waves with an effective pressure amplitude  $P$  and reference quantity  $P_{\text{ref}}$ , the sound pressure level is

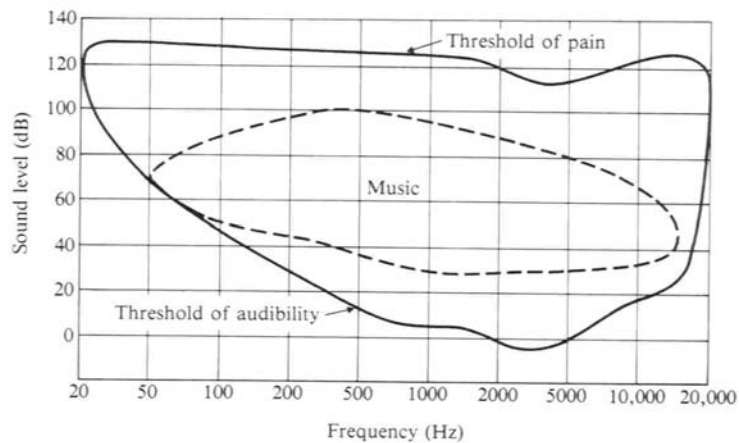
$$\text{SPL} = 10 \log_{10} (P/ P_{\text{ref}})^2$$

and is expressed as “dB re  $P_{\text{ref}}$ ”.<sup>4</sup> When the standard reference pressure corresponding to an intensity of  $10^{-12} \text{ W/m}^2$  is used, the statement of reference value is unnecessary, and is usually omitted by convention. Below are some typical SPLs of easily recognized sound sources.

SPL (dB)	Typical Sound
120	Jet aircraft takeoff at 60m
110	Construction site
100	Shout at 1.5m
90	Heavy Truck at 15m
80	Urban street
70	Automobile interior
60	Normal conversation at 1m
50	Office / classroom
40	Living room
30	Bedroom at night
20	Broadcast studio
10	Rustling leaves

**Table 1:** Sound pressure levels of typical sounds.<sup>5</sup>

Pain and audibility thresholds for the human ear are shown below.



**Figure 2:** Approximate range of frequency and sound level of music compared to the total range of hearing.<sup>6</sup>

**Decibel Scales**

Human hearing has a frequency range from 20 Hz to 20,000 Hz and is most sensitive at 2700 Hz (the lowest natural resonance of the ear canal)<sup>7</sup> and least sensitive at low frequencies. To adjust the response of a sound level meter, frequency-weighting scales are used. The most often used weighting scale (and the scale used in almost all noise standards) is the A scale, expressed as dBA or dB(A); it approximates the response of the human ear to moderate level sounds and includes a large low-frequency drop-off. The C scale approximates the response to high level sounds, and incorporates small drop-offs at both low and high frequencies. Despite the fact that this study deals with high level sounds, A weighting is used throughout for comparison with noise exposure standards.

Octave-center Frequency (Hz)	Weighted Response (dB)	
	A scale	C scale
31.5	-39.4	-3.0
63	-26.2	-0.8
125	-6.1	-0.2
250	-8.6	0
500	-3.2	0
1000	0	0
2000	1.2	-0.2
4000	1.0	-0.8
8000	-1.1	-3.0
16000	-6.6	-8.5

**Table 2:** Sound level meter weighting responses.<sup>8</sup>

**Equal Energy Hypothesis**

Many in the hearing loss community subscribe to the equal energy hypothesis, although there is some evidence to support other hypotheses. The premise behind the equal energy hypothesis is that “equal amounts of sound energy will produce equal amounts of hearing impairment regardless of how the sound energy is distributed in time”.<sup>9</sup> Therefore, one must determine the exchange rate, or doubling rate, of sound energy<sup>10</sup>. The energy is proportional to sound intensity and to the square of sound pressure. From the description of SPL above and assuming an exchange rate R,

$$\text{SPL} = 10 \log_{10}(\text{P}/\text{P}_{\text{ref}})^2$$

$$10 \log_{10}(\text{P}/\text{P}_{\text{ref}})^2 + \text{R} = 10 \log_{10}(\sqrt{2}\text{P}/\text{P}_{\text{ref}})^2$$

$$\text{R} = 10 \log_{10}(\sqrt{2}\text{P}/\text{P}_{\text{ref}})^2 - 10 \log_{10}(\text{P}/\text{P}_{\text{ref}})^2$$

$$\text{R} = 10 \log_{10}(\sqrt{2})^2$$

$$\text{R} = 10 \log_{10}(2)$$

$$\text{R} = 3.01 \approx 3$$

The result is that SPL increases by 3 dB whenever the sound energy doubles. As of May 2004, a 5 dB exchange rate is enforced in workplace regulations. This higher rate is less protective than the 3 dB rule and attempts to account for the interruptions in noise exposure that occur throughout a typical workday (breaks, meals, trips to the restroom, etc.). The National Institute of Occupational Safety and Health (NIOSH) recommends the 3 dB exchange after reviewing more recent data than was used to establish the 5 dB guidelines. The 3 dB exchange rate is appropriate to the scope of this research discussion because music is a mix between impulsive and continuous noise, and periods of reduced noise levels during band rehearsals only last for brief periods of time (typically less than one minute). In this study, comparisons will be made to the recommended NIOSH values using a 3 dB exchange rate.

### Time-Weighted Averages

A time-weighted average (TWA) is an average of different exposure levels over a period of exposure. Repeated studies have shown that there is low risk of hearing loss for exposures at or below 85 dBA. Therefore, the NIOSH recommendations are based on a safe 8-hour exposure to 85 dBA, called an 8-hour 85 dBA TWA. From this starting point, safe exposure lengths of time T in minutes for any 24-hour period can be calculated for any sound pressure level L in dBA<sup>11</sup>:

$$\text{T} = 480 / 2^{(L-85)/3}$$

Below are the combinations of exposure and duration that are considered safe.

Exposure (dBA)	Duration			Exposure (dBA)	Duration		
	Hours	Minutes	Seconds		Hours	Minutes	Seconds
80	25	24	--	106	--	3	45
81	20	10	--	107	--	2	59
82	16	--	--	108	--	2	22
83	12	42	--	109	--	1	53
84	10	5	--	110	--	1	29
85	8	--	--	111	--	1	11
86	6	21	--	112	--	--	56
87	5	2	--	113	--	--	45
88	4	--	--	114	--	--	35
89	3	10	--	115	--	--	28
90	2	31	--	116	--	--	22
91	2	--	--	117	--	--	18
92	1	35	--	118	--	--	14
93	1	16	--	119	--	--	11
94	1	--	--	120	--	--	9
95	--	47	37	121	--	--	7
96	--	37	48	122	--	--	6
97	--	30	--	123	--	--	4
98	--	23	49	124	--	--	3
99	--	18	59	125	--	--	3
100	--	15	--	126	--	--	2
101	--	11	54	127	--	--	1
102	--	9	27	128	--	--	1
103	--	7	30	129	--	--	1
104	--	5	57	130-140	--	--	<1
105	--	4	43	--	--	--	--

**Table 3:** NIOSH combinations of noise exposure levels and durations that no worker exposure shall equal or exceed.<sup>12</sup>

### **THE HISTORY OF NOISE REGULATION**<sup>13</sup>

In 1970, Congress passed Public Law 95-164, the Occupational Safety and Health Act. This law established the Occupational Safety and Health Administration (OSHA) within the Department of Labor. According to the Act, OSHA is responsible for protecting the safety and health of much of the workforce of the United States. The Act also established the National Institute for Occupational Safety and Health (NIOSH) within what is now the Department of Health and Human Services. NIOSH's purpose is to develop criteria for safe occupational workplace noise exposure.

In compliance with the Act, NIOSH published *Criteria for a Recommended Standard: Occupational Exposure to Noise* in 1972. This document recommended an exposure limit of 85 dBA as an 8-hour TWA using a 5 dB exchange rate, and discussed measuring, calculating, and preventing noise exposure. However, OSHA's initial guidelines were based on an exposure limit of 90 dBA as an 8-hour TWA, with a 5 dB exchange rate. Despite revisions of the OSHA guidelines throughout the 1980s, permissible exposure limits continued to be based on 90 dBA for an 8 hour exposure, although current regulations require hearing conservation program implementation when the 8-hour TWA exceeds 85 dBA.

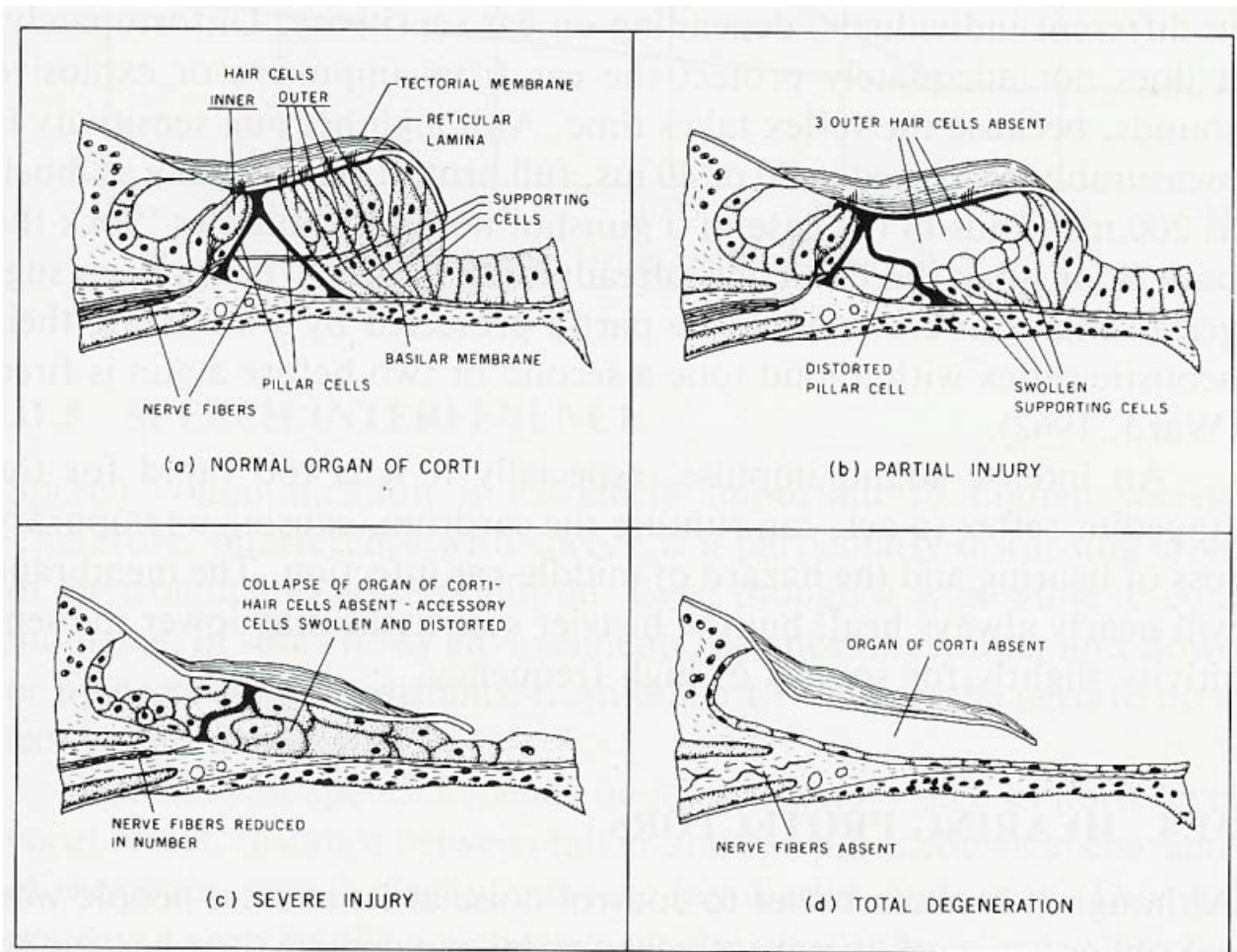
In 1998 NIOSH published *Criteria for a Recommended Standard: Occupational Noise Exposure – Revised Criteria 1998*. The revised document offers several major changes to the information presented in 1972; most notably, NIOSH now recommends a 3 dB exchange rate, for reasons previously discussed. The revision reaffirms the 85 dBA 8-hour TWA.

## **HEARING AND HEARING LOSS**

When exposed to noise, the eardrum vibrates. The eardrum changes the pressure variations of sound in air into mechanical vibrations, which are transmitted to the cochlea through three small bones called ossicles. The cochlea contains two membranes, Reissner's membrane and the basilar membrane, and resting on the basilar membrane is the organ of Corti, which contains thousands of hair cells. When the basilar membrane vibrates, the hair cells are excited and stimulate the auditory nerve; signals sent through the auditory nerve to the brain are interpreted as sound.<sup>14</sup>

Hearing loss occurs when the above process does not function normally. In most cases, including a musician's temporary or permanent hearing loss, this is because of damage to the hair cells.<sup>15</sup>

From extensive examinations of animal ears, and occasional post-mortem examinations of noise-damaged human ears, it has been fairly well established that excessive exposure to noise destroys the delicate hair cells in the organ of Corti and eventually the organ itself ... The mechanism by which the hair cells are destroyed is not completely clear ... One theory suggests that constant overexposure to sound forces the cells to work at too high a metabolic rate for too long a time, leading to the death of the cells. These delicate receptor cells do not regenerate, and if they die of overwork, they are lost for life.<sup>16</sup>



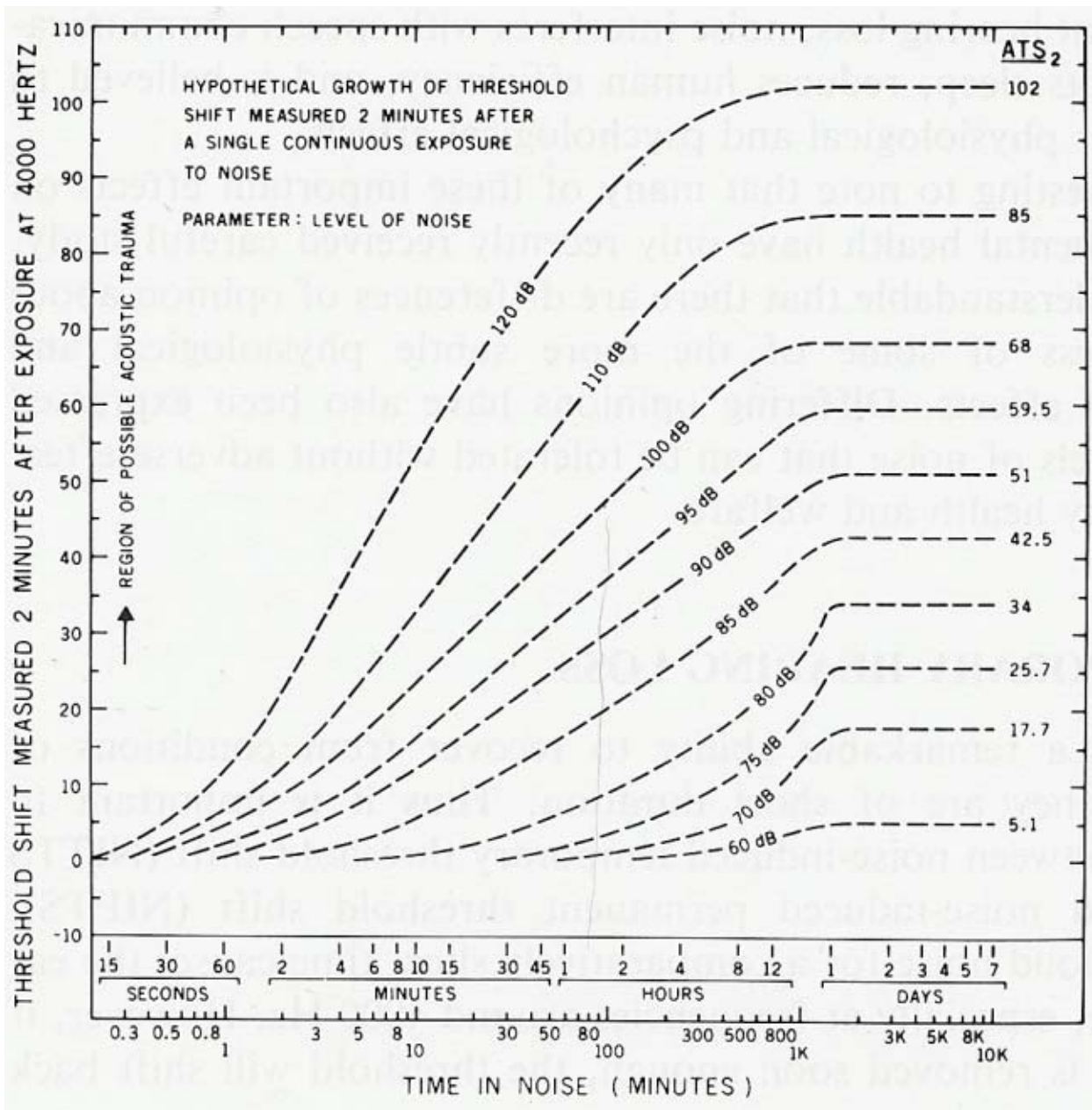
**Figure 3:** Drawings of the human organ of Corti that illustrate increasing degrees of noise-induced permanent damage.<sup>17</sup>

Hair cell damage can either be temporary, which results in a temporary threshold shift (TTS), or permanent, which results in a noise-induced permanent threshold shift (NIPTS). The following facts are presented for the reader to gain a general understanding of the effects of noise on TTS and NIPTS:

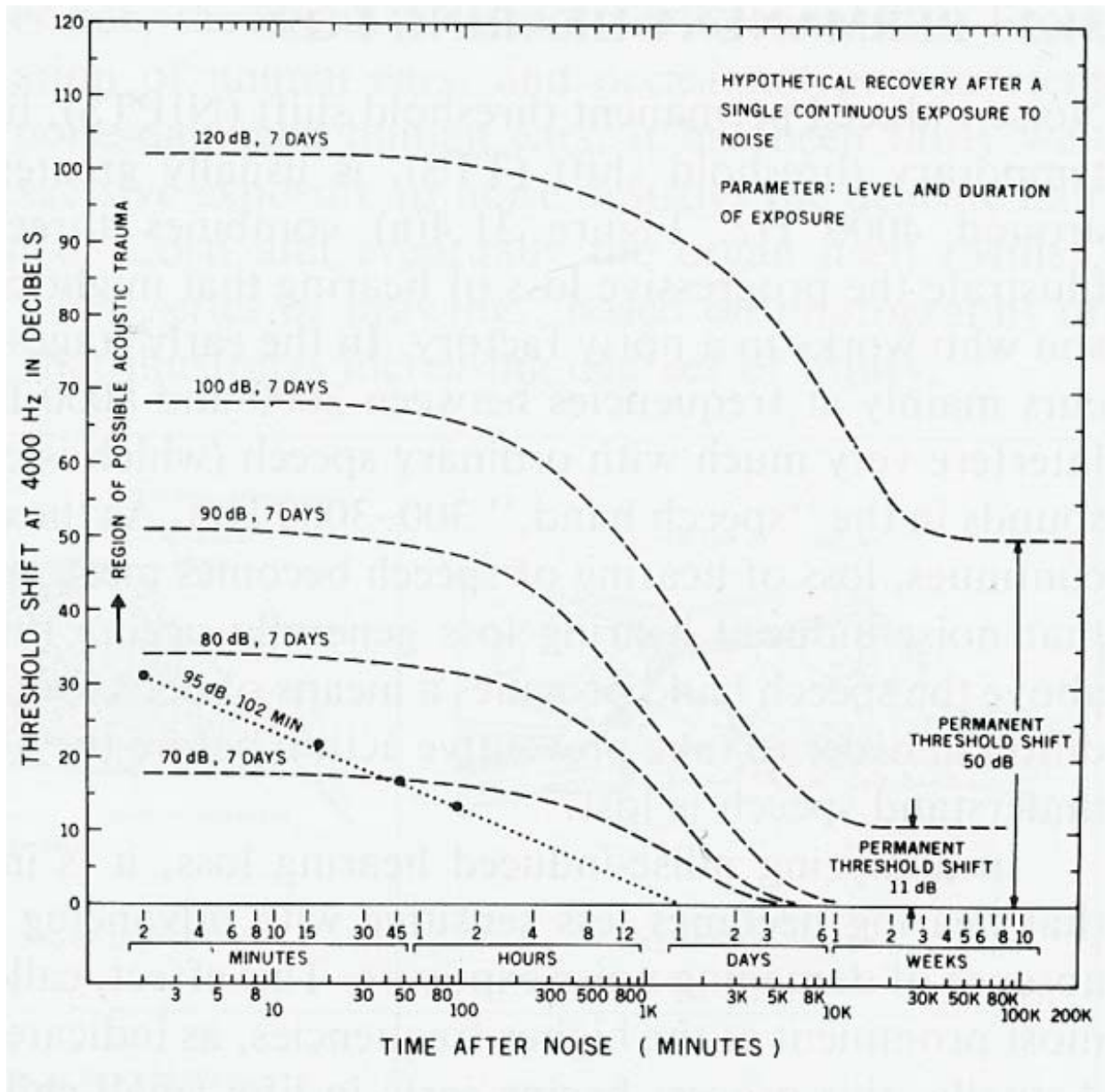
- The most damaging frequencies to the ear are between 2,000 and 4,000 Hz.<sup>18</sup>
- Impulsive noises cause less TTS or NIPTS in a free field than they do in an enclosure and/or under reverberant conditions.<sup>19</sup>
- “There is considerable variability among individuals in susceptibility to temporary hearing loss, the rate at which temporary hearing loss approaches its asymptotic level, and in the rate of recovery.”<sup>20</sup>

- An experiment showed that TTS “did not increase as exposure duration was increased from 8 to 48 hours; however, the time required for recovery from these longer exposures required several days of quiet.”<sup>21</sup>.
- If recovery from a TTS is not complete before the next exposure, some of the loss may become permanent.<sup>22</sup>
- TTS is most pronounced at frequencies slightly above the predominant frequency of the noise exposure.<sup>23</sup>
- “It is estimated that NIPTS usually reaches its maximum, depending on the intensity of the noise, following up to 20 years or so of near daily exposure to a given noise environment.”<sup>24</sup>
- “It has been shown repeatedly that when the interval between impulses becomes less than one second, the TTS does not increase, and sometimes decreases ... This phenomenon is undoubtedly related to action of the aural reflex and may possibly afford some protection against threshold shift from gun noise.”<sup>25</sup> The aural reflex, or acoustic reflex, is defined as the stapedius muscle contracting in response to a high-energy impulse, pulling the stapes (one of the ossicles) away from the cochlea while the tensor tympani muscle similarly restrains motions of the eardrum.
- “... when the interval between impulses increases beyond a certain point, the recovery from auditory fatigue between impulses permits a net decrease in TTS for a given total number of impulses.”<sup>26</sup>
- It is unclear what the delay required after intense auditory stimulation is in order to reduce the level of TTS.<sup>27</sup>

Below are figures representing the hypothetical growth and recovery from temporary threshold shifts due to exposures at various levels over various amounts of time. The figures are based on data from several laboratories and on extrapolations from data from animals.<sup>28</sup>



**Figure 4:** Hypothetical growth of temporary threshold shift due to exposure to noise of varying level and duration.<sup>29</sup>



**Figure 5:** Hypothetical recovery from various threshold shifts.<sup>30</sup>

Due to lack of complete data and ethical issues with human experimentation, these curves are only educated estimations. Also, the curves represent worst case scenarios, because the exposure noise was centered at 4000 Hz (where the ear is most susceptible to damage) and the threshold drop is measured at 4000 Hz (where threshold drops are large).<sup>31</sup> However, these curves, when compared with the data to be presented, indicate an extremely high probability of TTS due to participation in marching band, and indicate a significant chance of NIPTS over time. Although most of the recovery curves are drawn for 7 days of exposure, the single dotted

curve represents an estimated recovery from a 102-minute exposure to 95 dB<sup>32</sup>, which is on the order in both time and exposure level of a marching band rehearsal.

## **EXPERIMENTAL APPROACH - OVERVIEW**

### **Instrumentation**

A Larson Davis System 824 Precision Sound Level Meter and Real Time Analyzer was used to record A-weighted SPLs while the Duke University Marching Band and the Riverside High School (Durham, NC) Marching Band rehearsed and performed. The System 824 (Serial Number 1545) was factory calibrated May 23, 2002, certificate #2002-41800, and undergoes periodic field calibrations using a Larson Davis CAL200 (94/114 dB) at 1 kHz, which was factory calibrated April 7, 2003.

Levels were recorded as  $L_{eq}$  values (equivalent levels), in 1/3 octave bands, integrated over various time intervals. An  $L_{eq}$  can be thought of as a time average; the listener would be exposed to the measured SPL during the duration of the measurement if he or she listened to constant-volume noise at the level of the  $L_{eq}$  for the time of that measurement.

Below is the description from the System 824's manual detailing the mathematical process for collecting and determining  $L_{eq}$  data:

$$L_{Aeq,T} = 10 \lg \left\{ \left[ \frac{1}{T} \int_{t_1}^{t_2} p_A^2(t) dt \right] \div p_0^2 \right\} \text{dB}$$

**Figure 6:** The  $L_{eq}$  Integration performed by the System 824 Real Time Analyzer.<sup>33</sup>

$L_{Aeq,T}$  is the equivalent, continuous A-weighted sound pressure level re 20  $\mu$ Pa, determined over a time interval  $T = t_2 - t_1$ .  $p_A(t)$  is the instantaneous A-weighted sound pressure of the sound signal.  $p_0$  is the reference sound pressure of 20  $\mu$ Pa.

Measurements were taken from September 2003 through April 2004. For all measurements the microphone of the System 824 was either placed on a tripod or affixed to an extension, depending on whether the measurement was inside or outside, moving or stationary. The goal in all cases was to place the microphone as close to a band member's head position as possible without interfering with his or her duties as a band member. The researcher used his

extensive personal knowledge of marching band (9 years of experience) to gather data in as realistic an environment as possible. The researcher was a member of the Duke University Marching Band at the time of data collection and marched extensively with this band and with the Riverside band while gathering data in field measurements.

### **Data Display**

In all tables listing measured SPLs, levels are listed along with their respective locations (in terms of who is being exposed), principal sources of the exposure (in addition to the instrument at that location itself), sample times, and exposure times. In most cases exposure times are estimated; the researcher's duties to the Duke band as a percussionist and limited rehearsal times for all bands in general necessitated that multiple measurements be taken in each rehearsal for which data was being collected. For example, if a measurement was recorded over a period of 10 minutes, but the rehearsal conditions under which it was recorded lasted 2 hours, the estimated exposure time is listed as 2 hours. Multiple sample times ranging from seconds to hours for similar conditions substantiate the validity of accurately extrapolating a shorter sample to a lengthier exposure.

Exposure levels are compared with the 1998 NIOSH recommendations and are colored green, orange, or red. Data are presented according to whether they present no risk for the duration of the measurement or the estimated exposure time (green), risk for the estimated exposure time but not the duration of the measurement (orange), or risk for both the duration of the measurement and the estimated exposure time (red).

### **EXPERIMENTAL RESULTS – INDOOR REHEARSALS**

Participating in marching band necessitates successful attention to individual intonation, individual timbre and tone quality, ensemble intonation and blending, memorized relative and absolute locations within drill forms, drum major conducting, and either memorized music or reading music that is carried with the instrument. Inside rehearsals relieve many of these burdens and allow focus on the remaining difficulties, but often place band members at serious risk. Loud music, "lively" acoustical situations (hard floors, walls and ceilings), close proximity to other

instruments, and lack of desire to play outdoor music at an “indoor volume” (and thus differently from its intent during performance) are the main reasons that bands exceed safe SPLs indoors. Indoor rehearsals that include marching percussion (the drumline) also result in higher SPLs and more hearing loss risk than rehearsals without marching percussion.

In the tables showing exposure levels, microphone locations are listed along with the source of the most significant exposure other than the instrumentalist for whom the measurement was being taken; typical sources of exposure from other instruments are a trumpet playing towards a woodwind player or a marching percussionist playing near anyone seated next to a drum. Due to reflective and diffusive conditions indoors, one would expect any particular musician to be exposed by the entire band; therefore, only direct exposure from other instruments is listed.

### **Indoor Rehearsals - Duke**

The Duke band conducts indoor rehearsals in Bone Hall, a tiered rehearsal hall. Bone Hall has a floor of thin carpeting over three layers of rigid plywood. A shaped concrete diffuser wall covers the front wall and portions of the side walls; it consists of repeating patterns of DiffusorBlox<sup>®</sup> (“capable of providing broadband uniform sound diffusion in the horizontal plane for all angles of incidence”<sup>34</sup>). Heavy wooden storage closet doors make up the bottom of the rear wall, and thin wood makes up the top of the rear wall; curtains can be drawn to cover the top portion of the wall. Two-inch acoustically absorbent panels cover other portions of the side walls, and the remaining walls are solid concrete. The ceiling is coffered thick plaster and is suspended on resilient hangers beneath another heavy plaster ceiling for sound isolation from rooms on the floor above. The Duke band had 85 members in the 2003-2004 school year (5 flutes/piccolos, 8 clarinets, 12 alto saxophones, 4 tenor saxophones, 17 trumpets, 11 trombones, 6 mellophones, 2 baritones, 3 sousaphones, 3 snare drums, 2 tenors, 4 bass drums, 1 cymbals, 4 color guard members, and 3 drum majors), and rehearsed indoors approximately once every two weeks for 75 minutes.

Indoor rehearsal space (Bone Hall)  
 Duke University

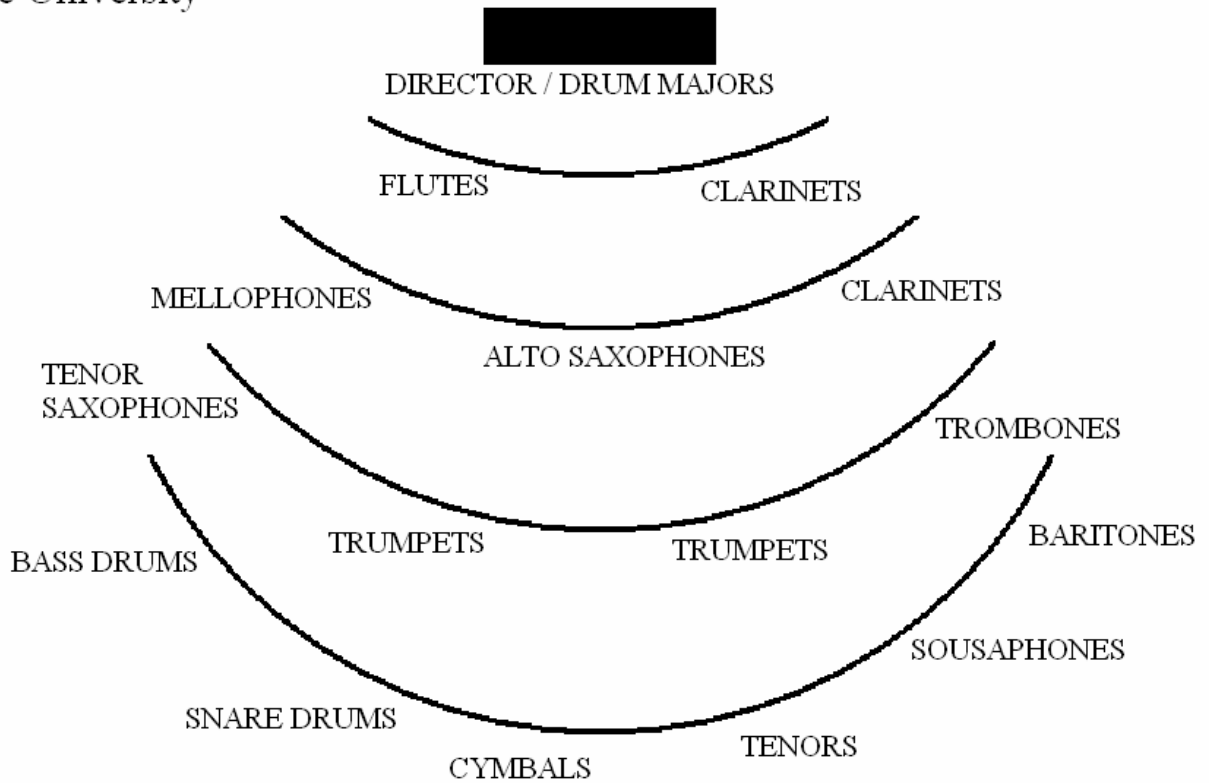
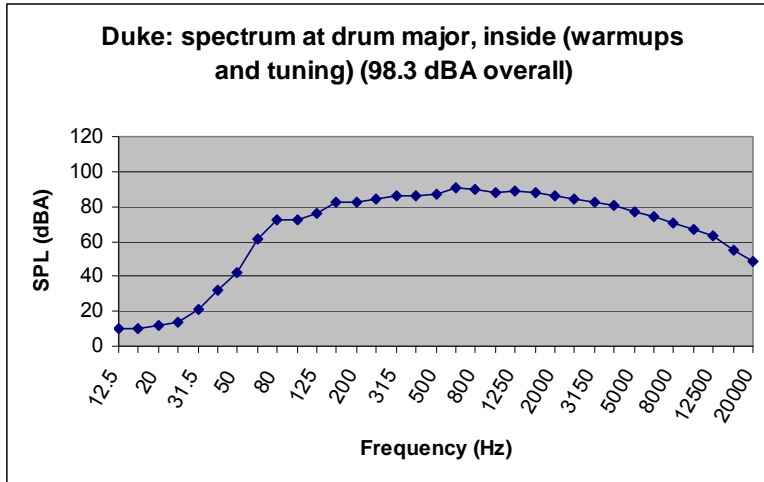


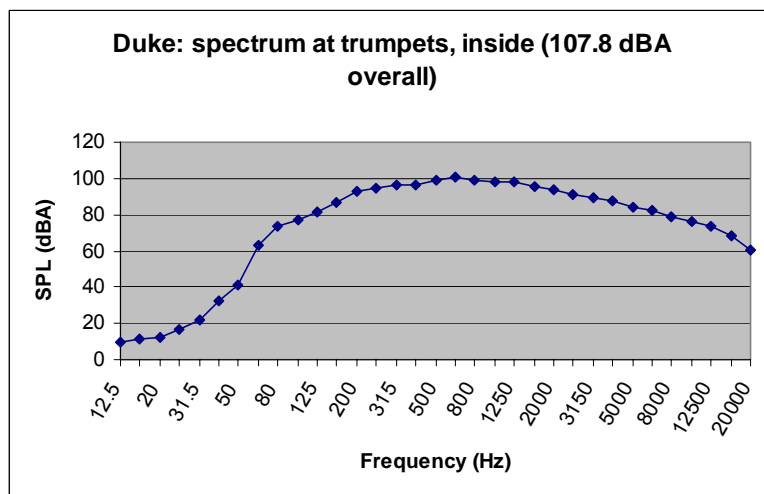
Figure 6: Duke University indoor rehearsal.

DUKE UNIVERSITY, WITH DRUMLINE				
SPL (dBA)	Location	Principal Sources of Exposure from other instruments	Sample Time	Exposure Time*
98.3	drum major (warmups and tuning)	entire band	0:12:21	0:12:21
98.8	between clarinets and alto saxophones	brass	0:11:45	(1:15:00)
99.4	tenor saxophones	marching percussion	0:07:32	(1:15:00)
99.6	flutes	mellophones, trumpets	0:09:32	(1:15:00)
100.2	drum major	entire band	<b>1:26:20</b>	<b>1:26:20</b>
103.6	alto saxophones	trumpets	0:11:13	(1:15:00)
104.1	between snare drums and bass drums	marching percussion	0:09:46	(1:15:00)
105.3	snare drums	marching percussion	<b>1:01:44</b>	<b>1:01:44</b>
106.0	cymbals	marching percussion	0:07:53	(1:15:00)
107.8	trumpets	marching percussion	0:09:19	(1:15:00)

Table 4: Duke University indoor rehearsal SPLs.  
 \*estimated exposure times are in parentheses



**Figure 7:** Drum major exposure from entire band.



**Figure 8:** Trumpet exposure from marching percussion.

As may be expected, the shapes of the spectra in Bone are all similar due to sound reflection and dispersion off of the walls. Above are the spectral curves for the minimal and maximal measurements. The highest levels recorded were at the ears of the trumpets due to the tiered seating in the room; the marching percussion standing behind the trumpets, combined with the trumpets being seated one tier below, puts trumpet players’ heads right at the level of the drums for a very high exposure level. In general, the highest levels in the Duke band originate from the marching percussion and from the trumpets.

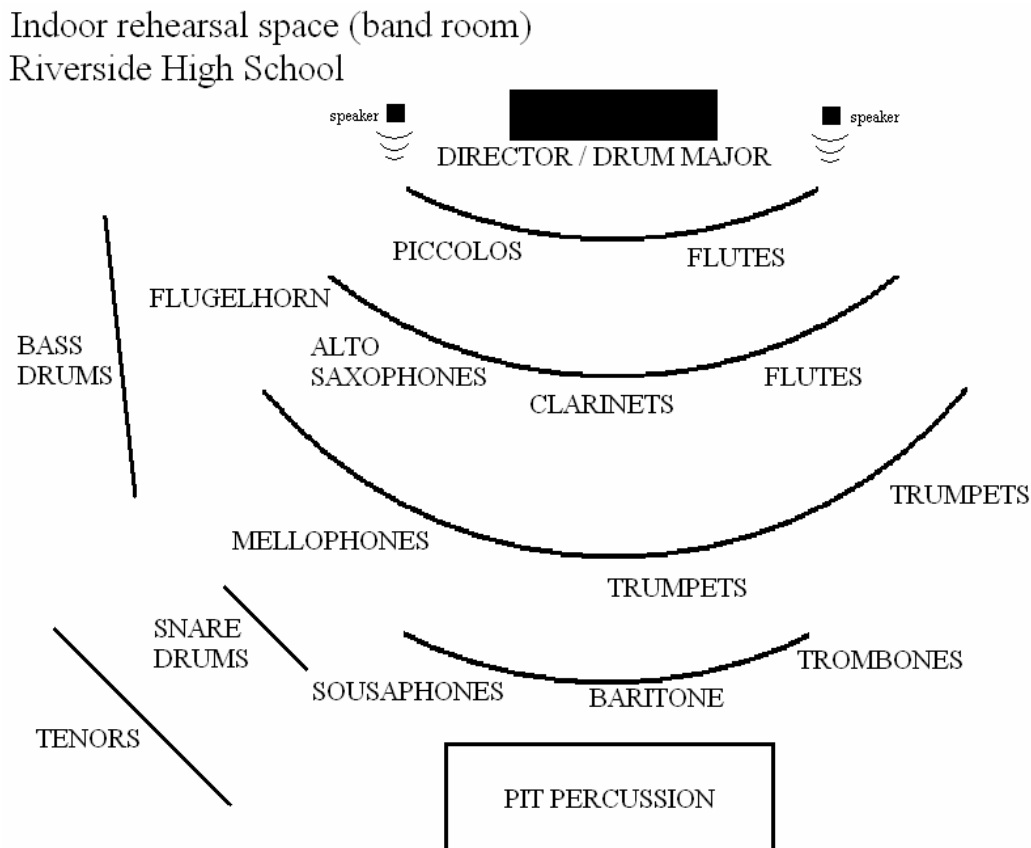
Care should be taken when interpreting “safe” data, such as the entry “drum major (warmups and tuning)” above. It is true that this datum shows no risk for the Duke drum majors while the band is warming up and tuning. However, the beginning of rehearsal does not last

forever. It would be a strange rehearsal indeed if the band did not switch to other music after warming up, and the data show that this other music comes with a higher SPL.

### Indoor Rehearsals - Riverside

The Riverside High School Marching Band conducts indoor rehearsals in a typical high school band room (i.e. thin carpet over a concrete floor, concrete walls with acoustically absorbent panels, and a paneled drop ceiling). The Riverside band had 61 members in the 2003-2004 school year (12 flutes/piccolos, 3 clarinets, 2 alto saxophones, 8 trumpets, 1 flugelhorn, 3 trombones, 3 mellophones, 1 baritone, 2 sousaphones, 2 snare drums, 2 tenors, 4 bass drums, 18 color guard members, and 1 drum major), and rehearsed inside three times per week for approximately 60 minutes each.

In the absence of a drumline, a click track was often used during indoor rehearsals; a digital metronome was played loudly through speakers to keep tempo. Measurements taken while the click track was in use are labeled with a “CT”. Below is a diagram of the Riverside band room seating arrangements.



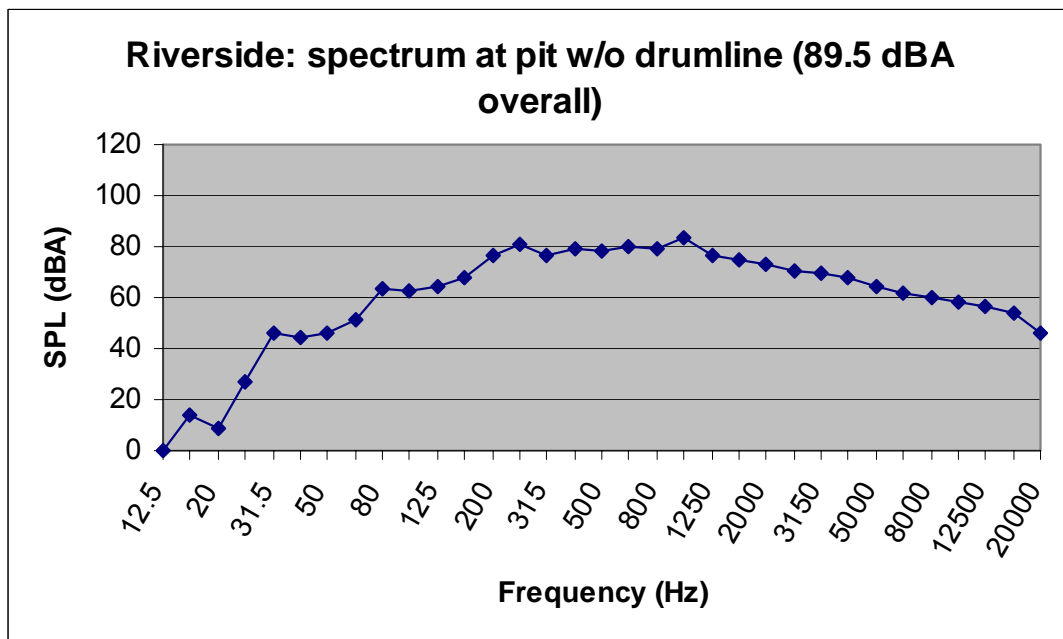
**Figure 9:** Riverside High School indoor rehearsal.

<b>RIVERSIDE HIGH SCHOOL, WITHOUT DRUMLINE</b>				
<b>SPL (dBA)</b>	<b>Location</b>	<b>Principal Sources of Exposure from other instruments</b>	<b>Sample Time</b>	<b>Exposure Time*</b>
89.5	pit	none	0:04:43	(1:00:00)
90.9	trumpets	trombones, CT	0:10:22	(1:00:00)
93.9	flutes (warmups and tuning)	trumpets	0:05:50	(0:10:00)
94.9	drum major	entire band, CT	0:06:31	(1:00:00)
95.0	flutes	alto saxophones, mellophones, CT	0:08:06	(1:00:00)
95.7	pit	CT	0:07:55	(1:00:00)
95.7	flutes	trumpets, CT	0:10:08	(1:00:00)

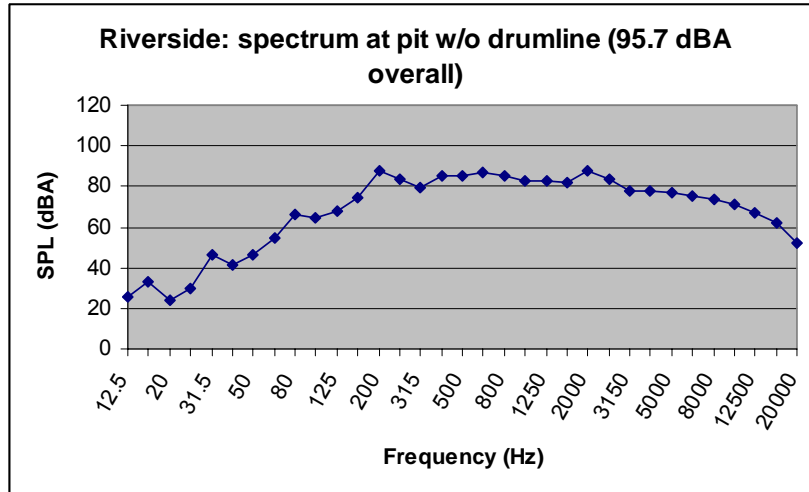
**Table 5:** Riverside High School SPLs for indoor rehearsals (without drumline).  
\*estimated exposure times are in parentheses

<b>RIVERSIDE HIGH SCHOOL, WITH DRUMLINE</b>				
<b>SPL (dBA)</b>	<b>Location</b>	<b>Principal Sources of Exposure from other instruments</b>	<b>Sample Time</b>	<b>Exposure Time*</b>
96.4	bass drums	marching percussion	0:03:42	(0:30:00)
96.5	tenors	marching percussion	0:01:26	(0:30:00)
100.2	flugelhorn	bass drums	0:01:01	(0:30:00)
100.5	sousaphones	marching percussion	0:01:31	(0:30:00)
101.5	between snare drums and bass drums	marching percussion	0:04:10	(0:30:00)

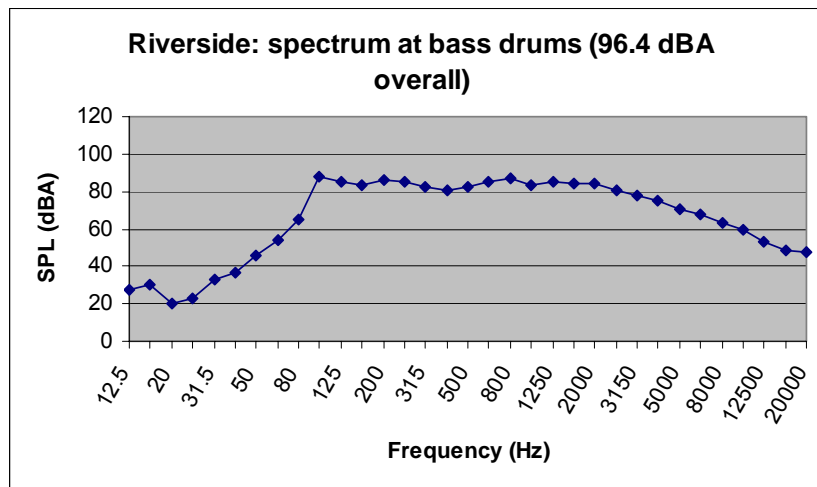
**Table 6:** Riverside High School SPLs for indoor rehearsals (with drumline).  
\*estimated exposure times are in parentheses



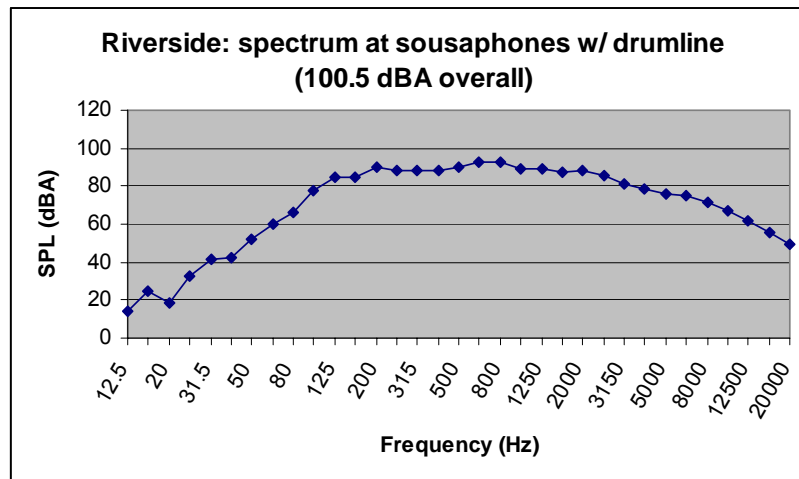
**Figure 10:** Pit exposure from no other principal source.



**Figure 11:** Pit exposure from click track.



**Figure 12:** Bass drum exposure from marching percussion.



**Figure 13:** Sousaphone exposure from marching percussion.

It appears that the most dangerous locations in full band rehearsals in the Riverside band room are anywhere close to the marching percussion section. Unfortunately, limited rehearsal time resulted in incomplete data, as there were no measurements taken away from the marching percussion. In rehearsals without marching percussion present, exposures vary from safe to dangerous in similar locations, indicating that exposure inside for a band rehearsing without marching percussion is very dependent on the type of music being rehearsed.

Regardless of the risk caused by the exposure level, all spectra recorded while the click track was being used show a peak in the 2000-2500 Hz range, at the frequency of the click track tones. Unfortunately this range is in the range that is most damaging to human hearing.

## **EXPERIMENTAL RESULTS - DRUMLINE REHEARSALS**

The marching percussion section differs from the rest of a band in that all of their notes are impulsive and exact. Because the drumline is so important to controlling the tempo of the band, and because the impulsive nature of striking drumheads can often make imprecise playing obvious even to the untrained listener, marching percussion sections often rehearse apart from the rest of the band in order to focus on these issues. Marching percussion instruments produce very high SPLs even without the rest of the band playing; the highest measurements recorded in any set were ones taken in, at, or near the drumline. High SPLs around marching percussion result mainly from high-tension drumheads made of sheet polyester (mylar), sometimes combined with Kevlar<sup>®</sup>, the same material from which bullet-proof vests were formerly constructed. These high-tensioned heads and various sized drums, producing waveforms with extremely steep onset slopes, combine to create a broadband high intensity sound environment in any rehearsal involving these instruments. When the drumline rehearses in areas with hard walls and floors, or worse, in areas surrounded by brick and concrete, the high SPLs are increased even further.

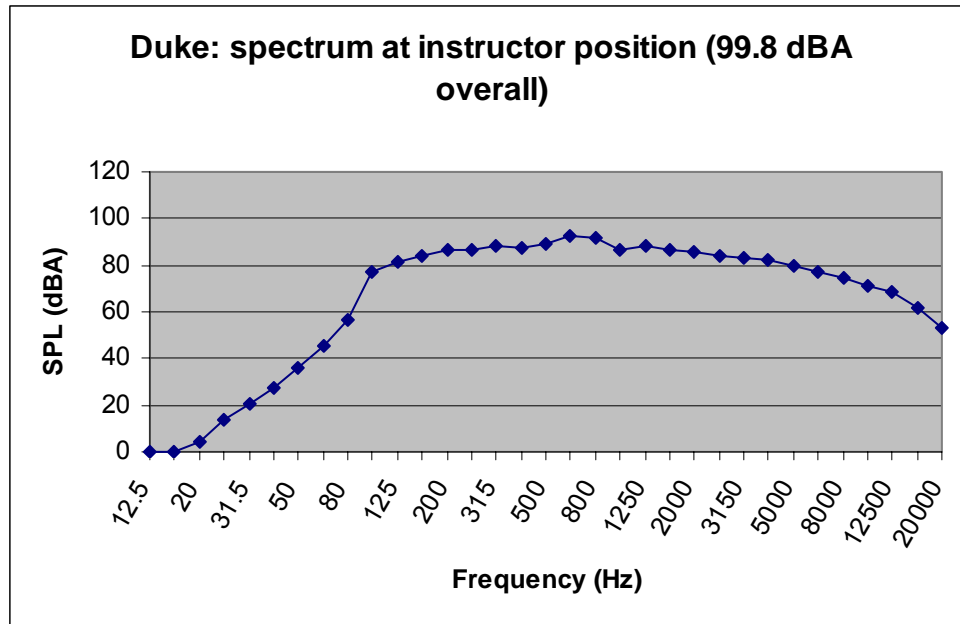
### **Drumline Rehearsals - Duke**

Duke drumline rehearsals rarely varied except in length over the course of the marching season; the drums were in the same place in the same room (Bone Hall, the same location as

during full band rehearsal). Drumline rehearsals took place approximately once per week for 90 minutes.

DUKE UNIVERSITY DRUMLINE, INDOORS			
SPL (dBA)	Location	Sample Time	Exposure Time
99.8	observer/instructor position (center of arc)	0:29:35	(1:30:00)

**Table 7:** Duke University SPLs for drumline rehearsals.  
\*estimated exposure times are in parentheses



**Figure 14:** Drumline instructor exposure from marching percussion.

The microphone for the measurement taken for Duke was located in the center of the drumline arc, where a percussion instructor would stand during rehearsal. However, the nature of playing marching percussion instruments in a room such as Bone Hall is such that unless you stand very close to a corner in the room or place your head in the extreme near field of a particular drum, exposure in general will be uniform throughout the room.

**Drumline Rehearsals – Riverside**

Riverside drumline rehearsals also took place in the same location throughout the season (in a courtyard located close to the band room). These rehearsals took place an average of twice a week for approximately 35 minutes, plus once a week for approximately 90 minutes.

Outdoor drumline rehearsal space (courtyard)  
Riverside High School

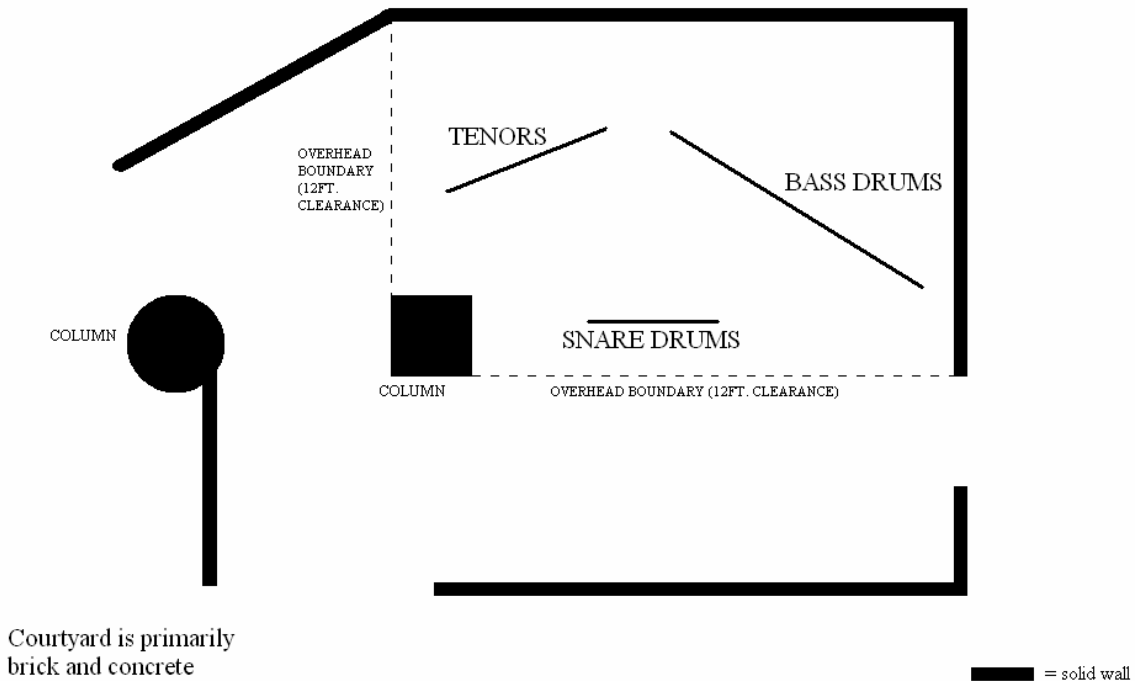


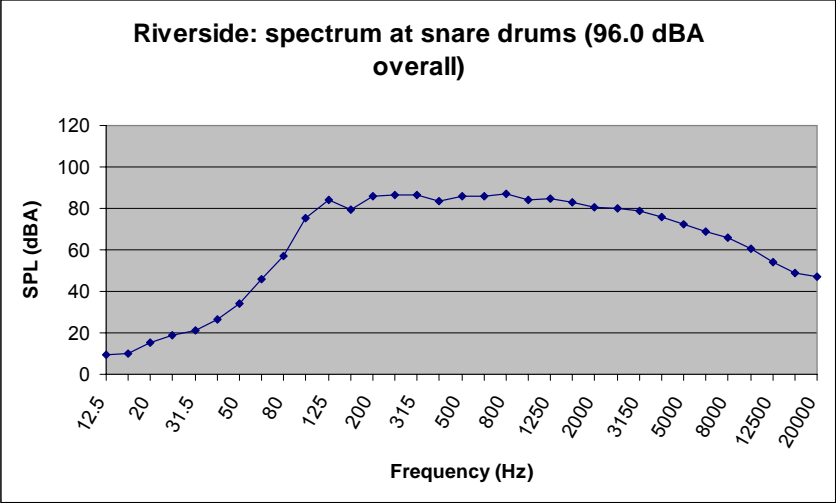
Figure 15: Riverside High School drumline rehearsal.

RIVERSIDE HIGH SCHOOL DRUMLINE, OUTDOORS			
SPL (dBA)	Location	Sample Time	Exposure Time*
93.6	behind bass drums (instructor)	0:01:34	(0:35:00)
96.0	snare drums	0:02:55	(0:35:00)
98.9	between snare drums and bass drums	0:14:46	(0:35:00)
103.0	bass drums	0:03:54	(0:35:00)
104.7	tenors	0:06:55	(0:35:00)

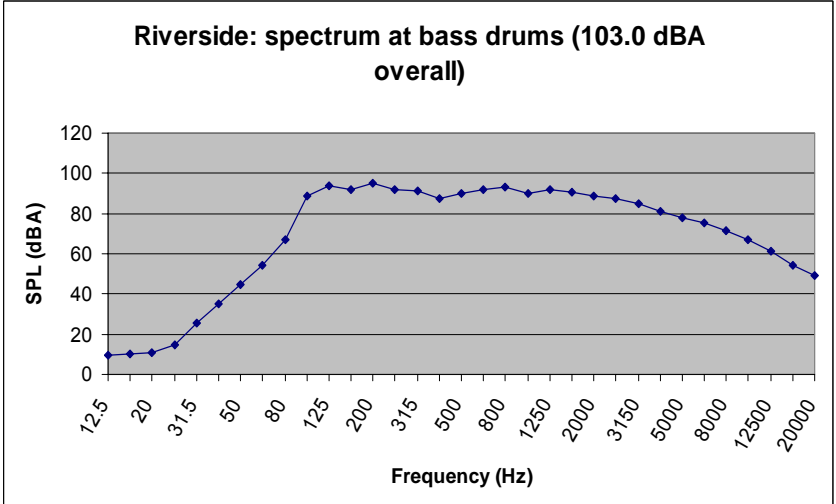
Table 8: Riverside High School SPLs for drumline rehearsals.

\*estimated exposure times are in parentheses

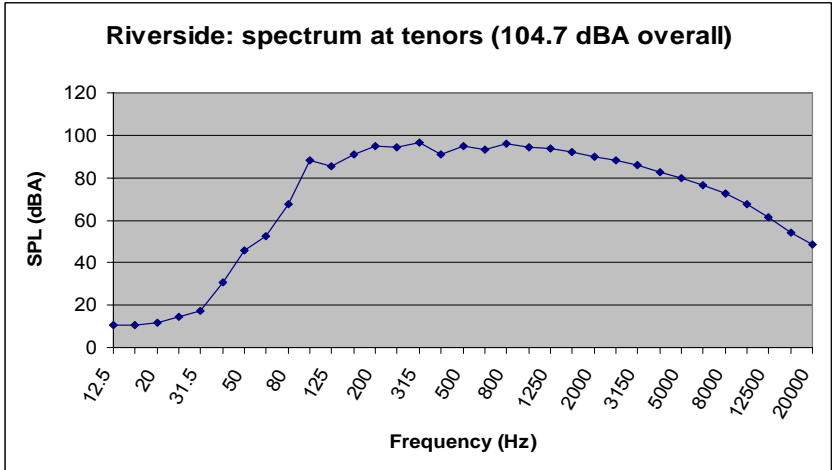
The Riverside data show that in a location with highly reflective surfaces, the proximity to the hard walls has a greater effect than the type and frequency of the drum. Thus, there are higher SPLs near the Riverside bass drums and tenors than there are at the snare drums, because the snare drums are located away from the back walls of the courtyard. Further proof that the location is more important than individual instruments in an extremely live acoustical situation lies in the spectra of the snare drums, tenors, and bass drums in the Riverside courtyard; the spectra of these three vastly different instruments are almost identical in shape and only vary in level.



**Figure 16:** Snare drum exposure from marching percussion.



**Figure 17:** Bass drum exposure from marching percussion.



**Figure 18:** Tenors exposure from marching percussion.

## **EXPERIMENTAL RESULTS - OUTDOOR REHEARSALS**

A Marching Band spends the majority of its rehearsal time in outdoor rehearsals, focusing on playing and moving at the same time. Exposures are not only a result of the length of time the band is playing, but of the changing locations of the instruments in relation to each other. Proximity to dangerous instruments and the high levels they produce is varying constantly, and depends entirely on the design of the marching drill.

### **Outdoor rehearsals – Riverside**

The Riverside band rehearsed outside on an asphalt parking lot with football field lines. Outdoor rehearsals took place 3 times per week for approximately 2 hours each. Just as inside, a click track was sometimes used, even when the drumline was participating; outside the click track was played through a portable speaker that varied in location. Below are exposure levels for outdoor rehearsals at Riverside, followed by selected drill sets that represent a continuous portion of one marching band tune. An in-depth analysis is undertaken in these seven pages of drill; each measured location is indicated with a colored box on the drill pages and is labeled with a number that corresponds to a measurement listed on the table of SPLs. While these drill charts present only a small portion of a band's repertoire and perhaps only a small portion of a rehearsal, the locations and SPLs presented in these data are typical of any marching band rehearsal.

f	flute / piccolo
c	clarinet
a	alto saxophone
t	trumpet
F (single)	flugelhorn
m	mellophone
T	trombone
b	baritone
S	sousaphone
s	snare drum
Q	tenors
X	bass drum
F (multiple)	color guard

**Table 9:** Riverside drill chart codes



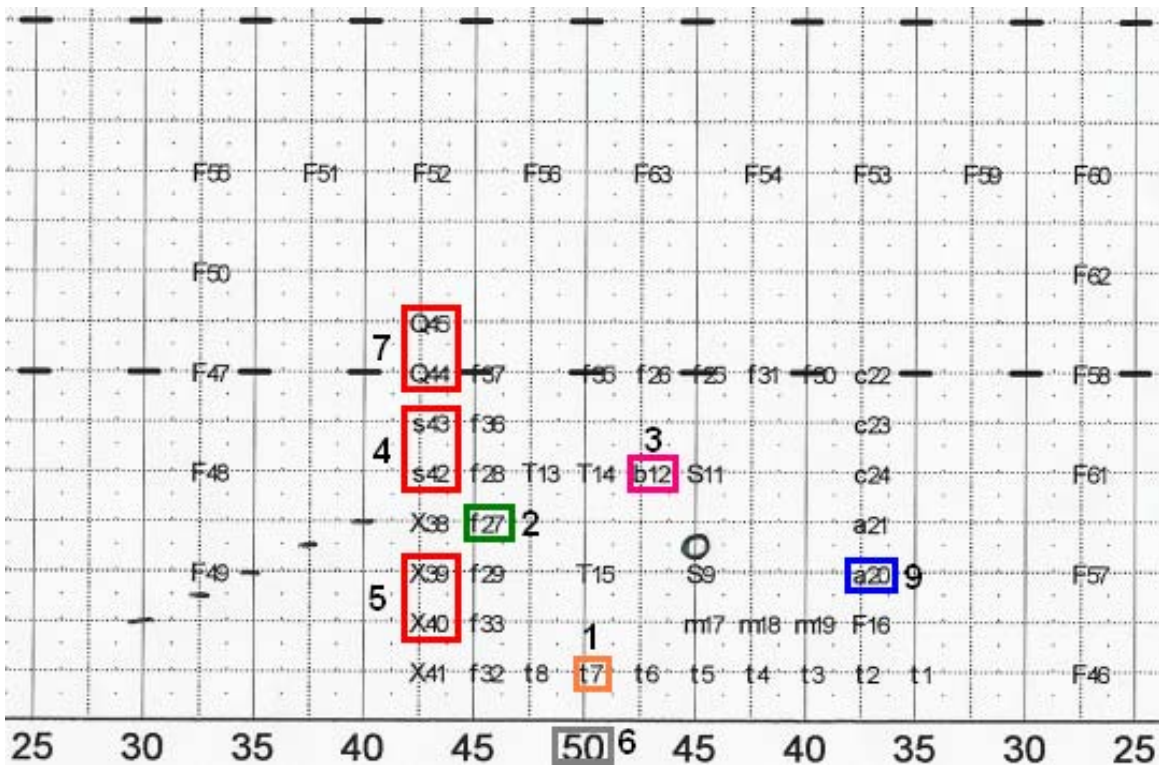


Figure 20: Riverside drill page 2

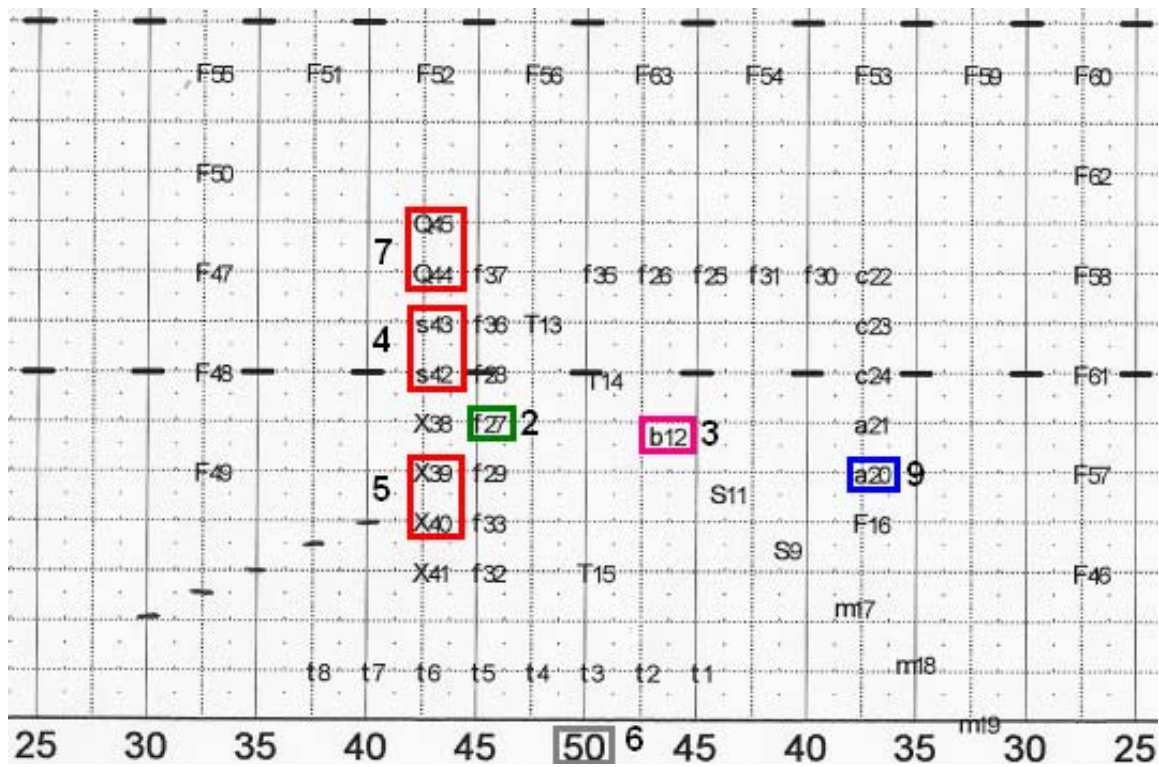


Figure 21: Riverside drill page 3

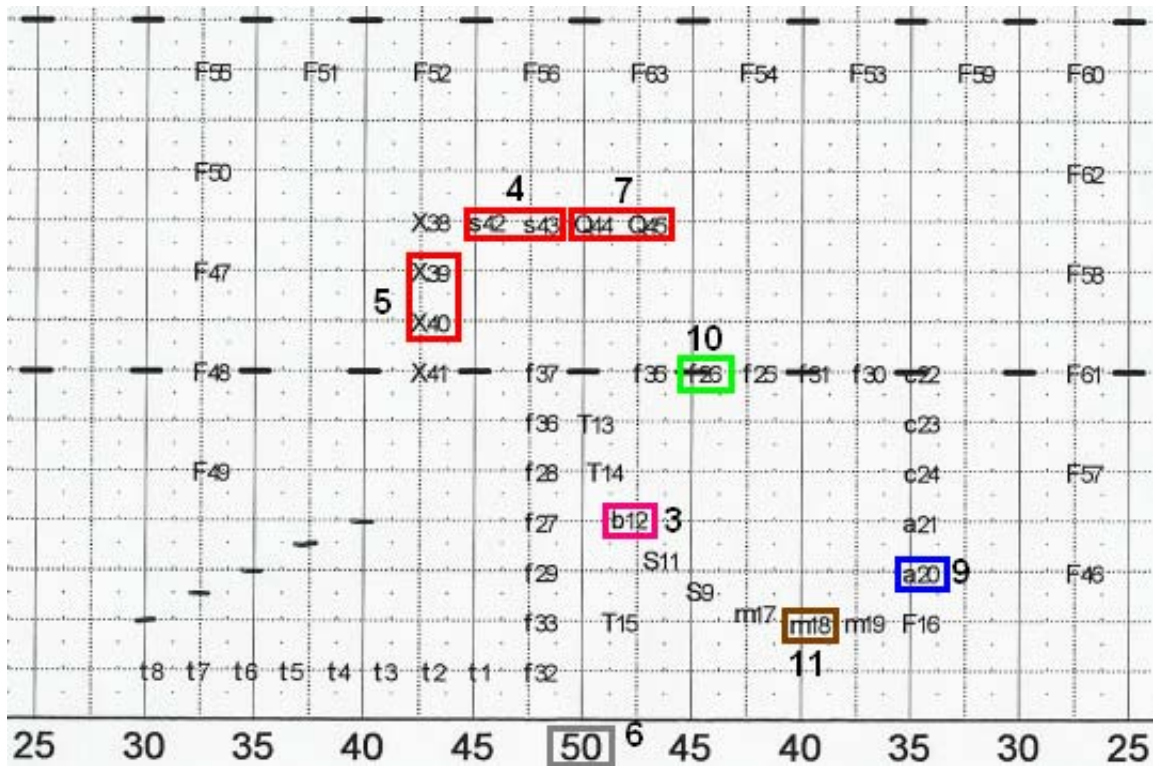


Figure 22: Riverside drill page 4

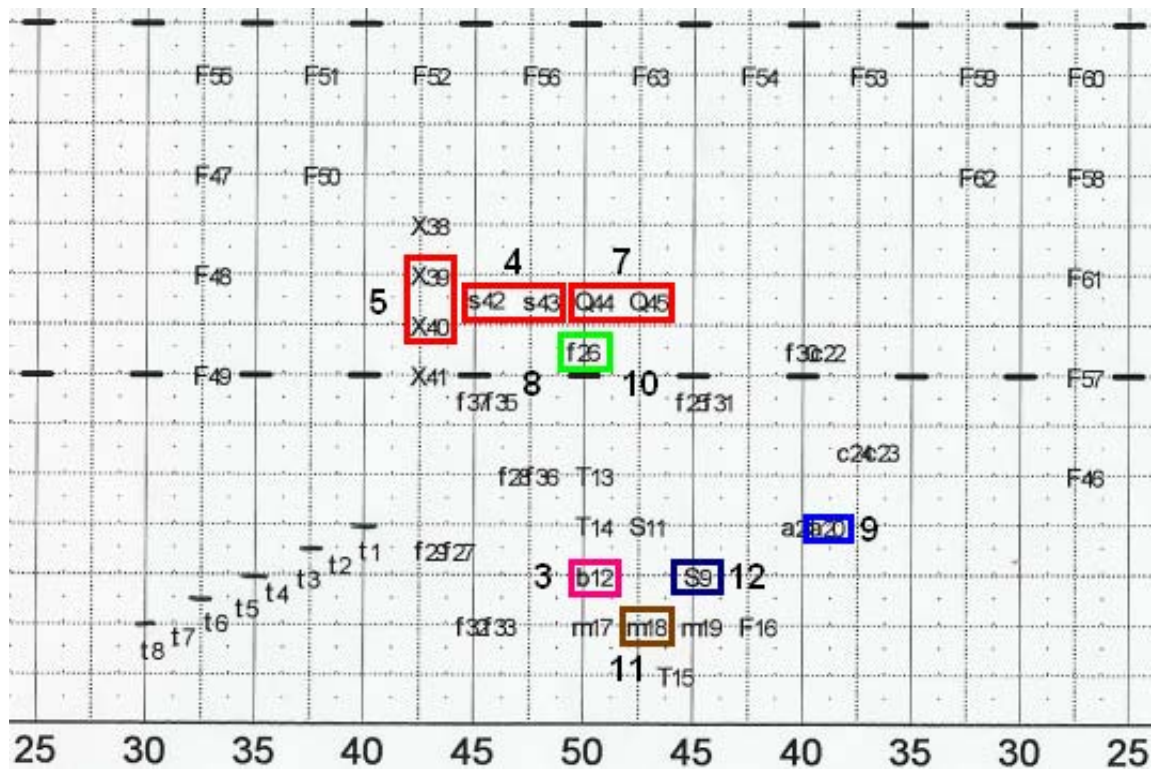


Figure 23: Riverside drill page 5

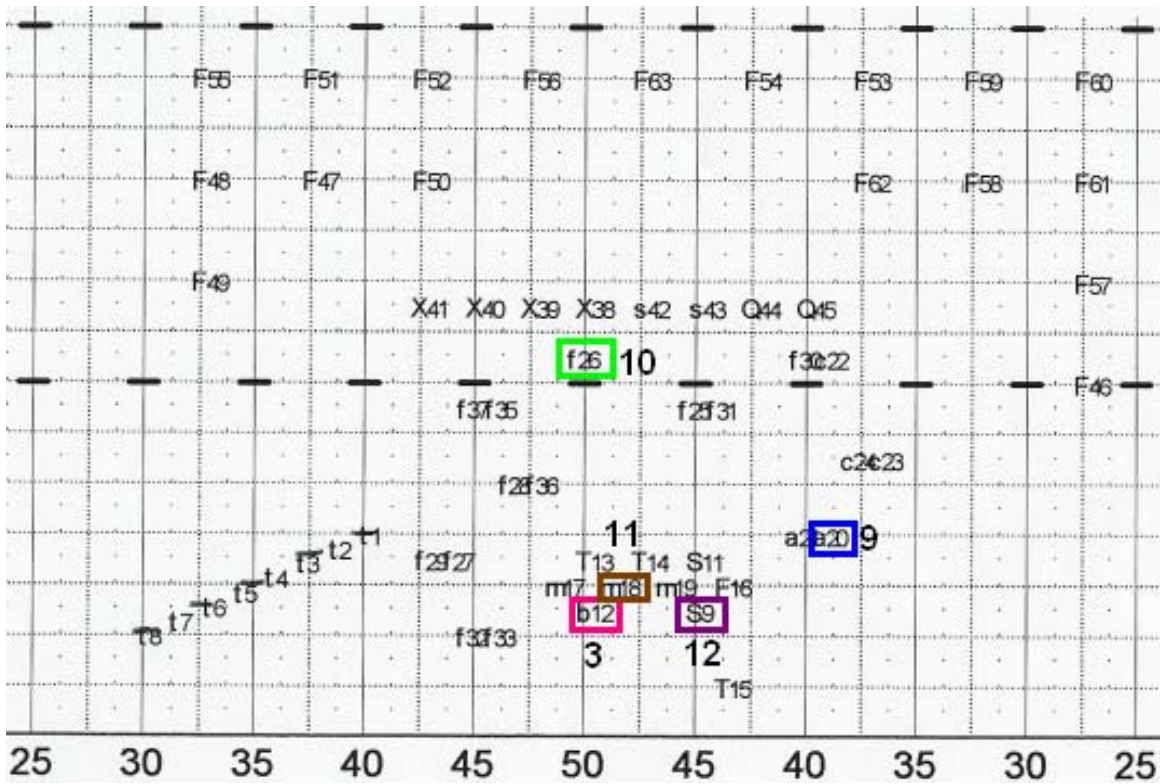


Figure 24: Riverside drill page 6

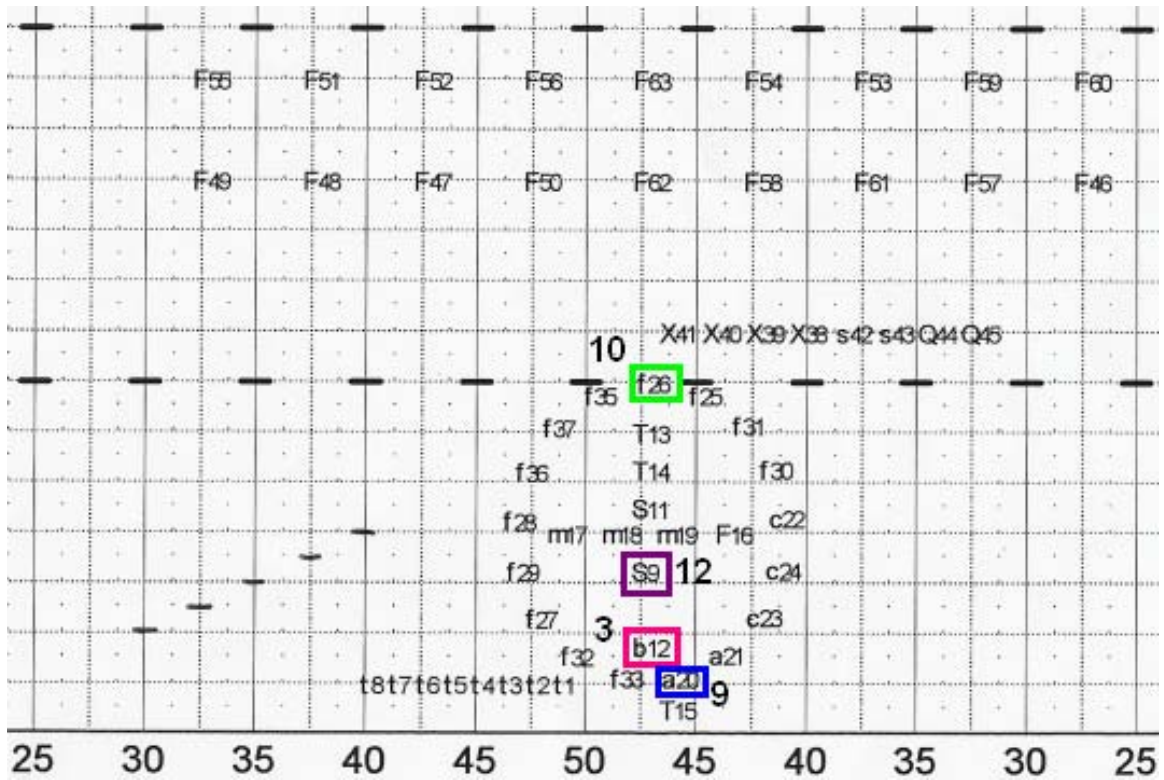
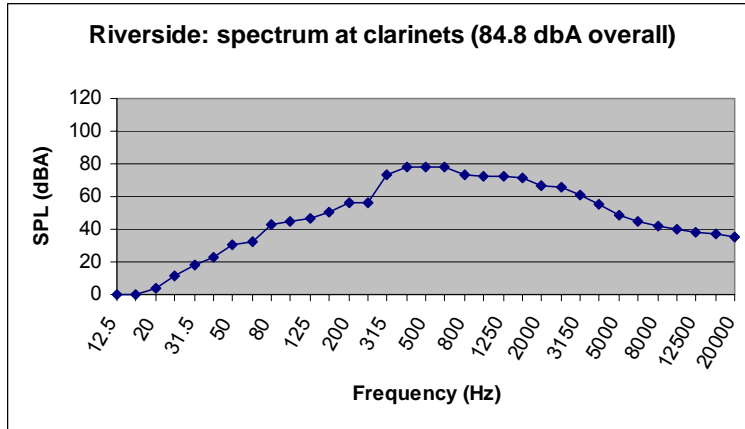
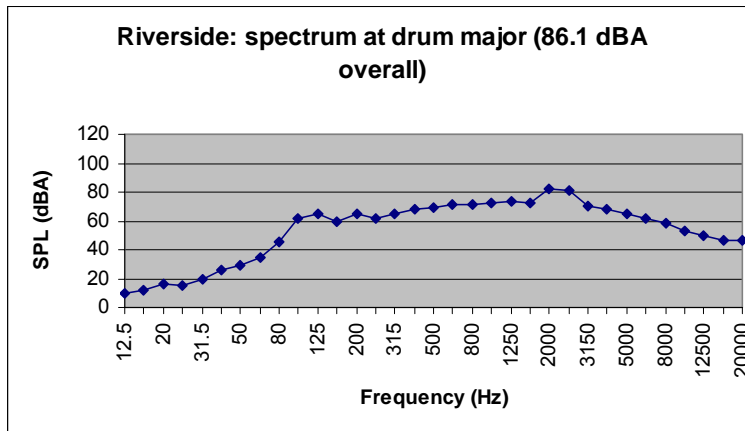


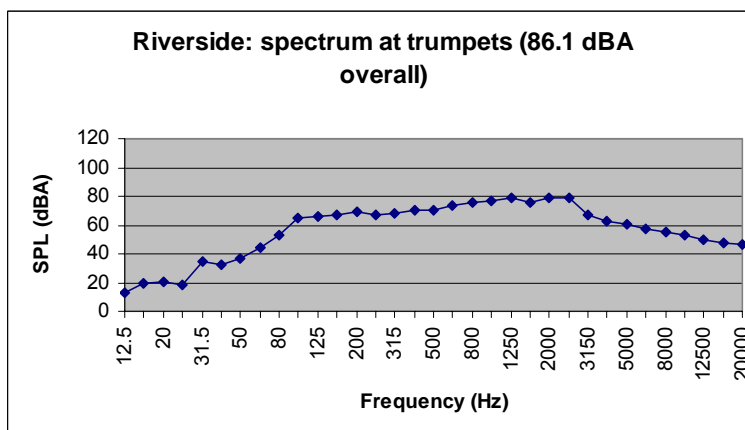
Figure 25: Riverside drill page 7



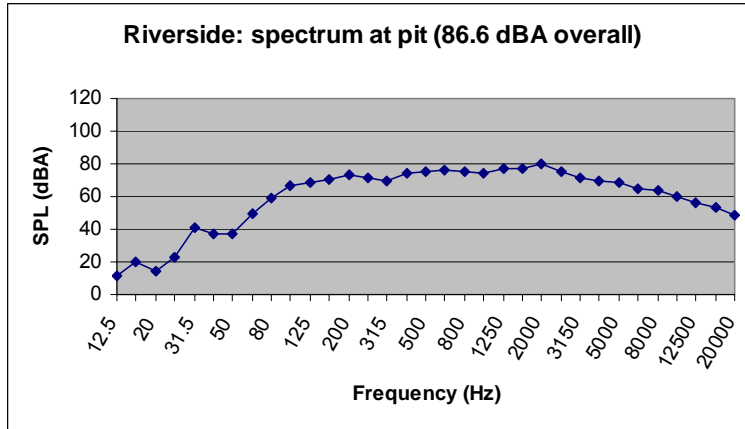
**Figure 26:** Clarinet exposure from no other principal source.



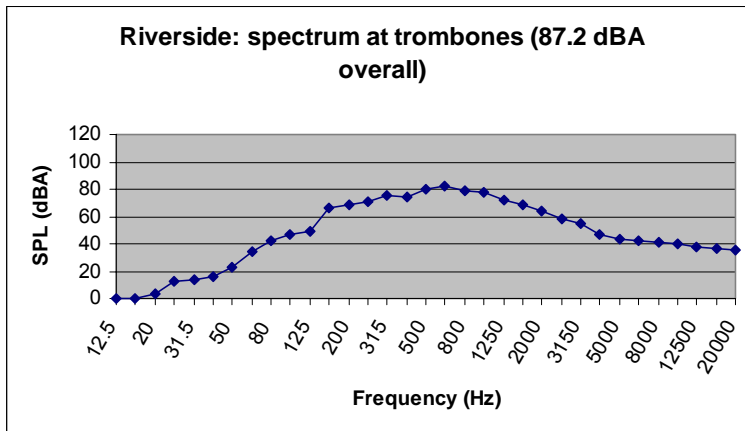
**Figure 27:** Drum major exposure from entire band and click track.



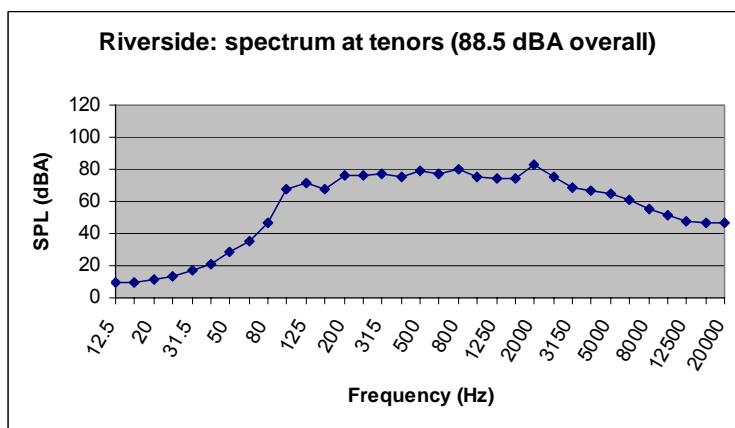
**Figure 28:** Trumpet exposure from entire band and click track (1).



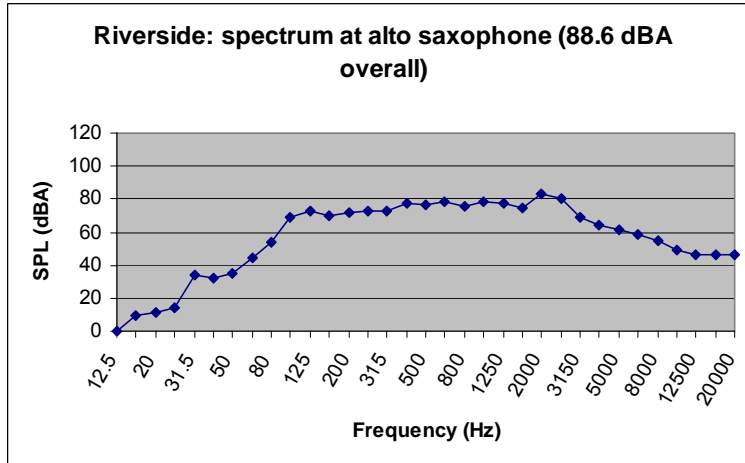
**Figure 29:** Pit exposure from trumpets and click track (6).



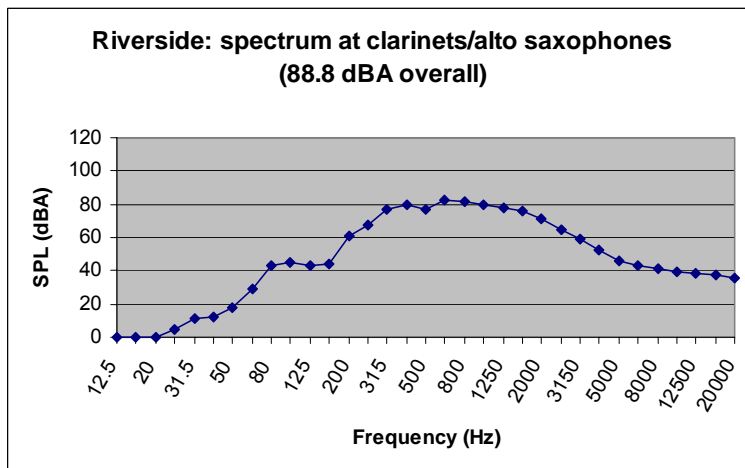
**Figure 30:** Trombone exposure from baritone and sousaphones.



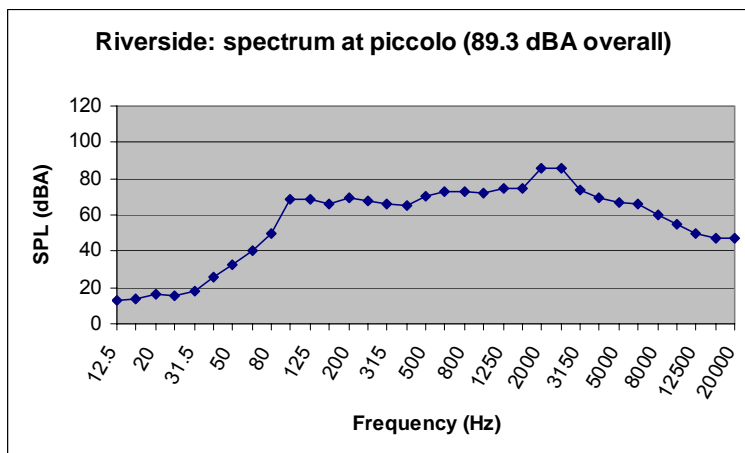
**Figure 31:** Tenors exposure from marching percussion and click track (7).



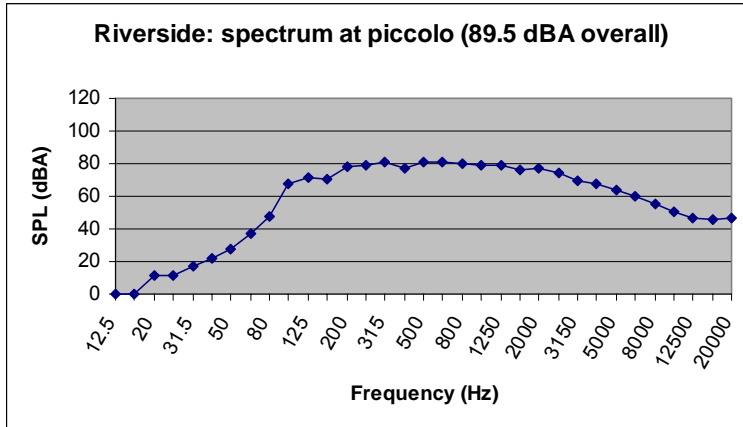
**Figure 32:** Alto saxophone exposure from low brass and click track (9).



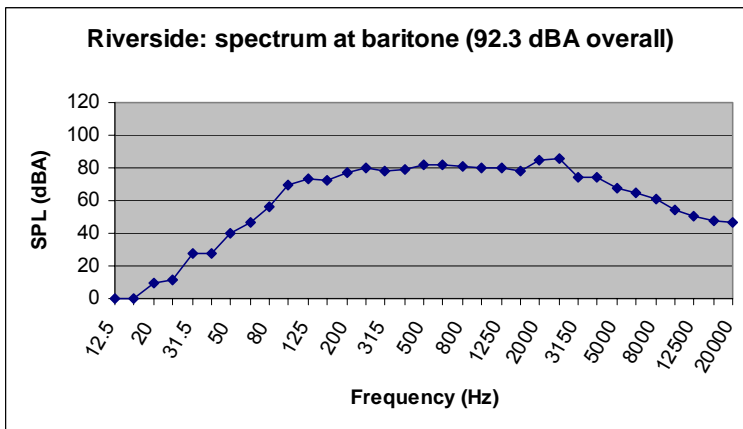
**Figure 33:** Alto saxophone and clarinet exposure from mellophones and trombones.



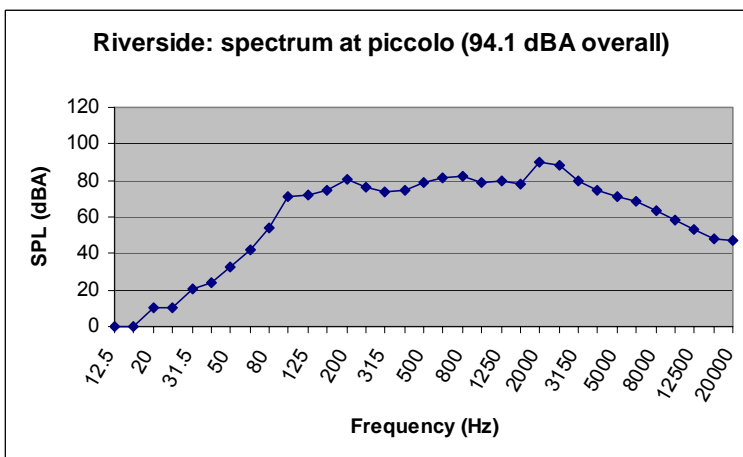
**Figure 34:** Piccolo exposure from marching percussion and click track (2).



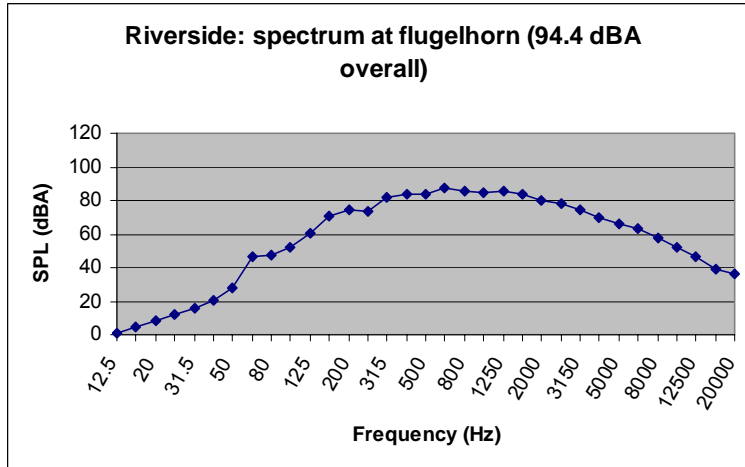
**Figure 35:** Piccolo exposure from marching percussion and click track (8).



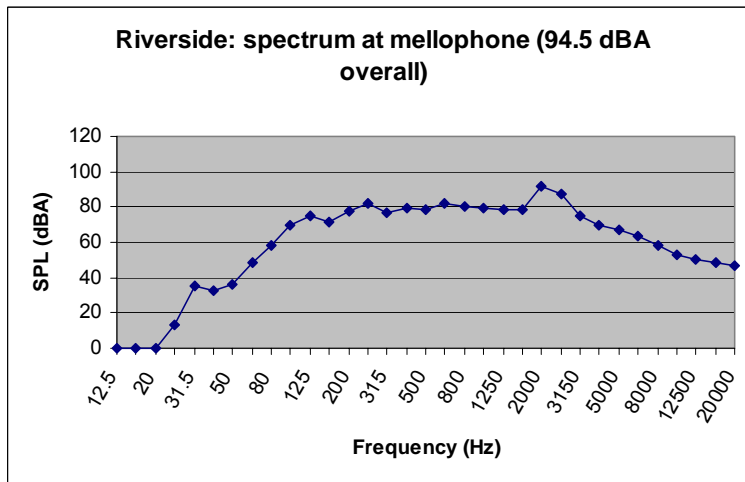
**Figure 36:** Baritone exposure from low brass and click track (3).



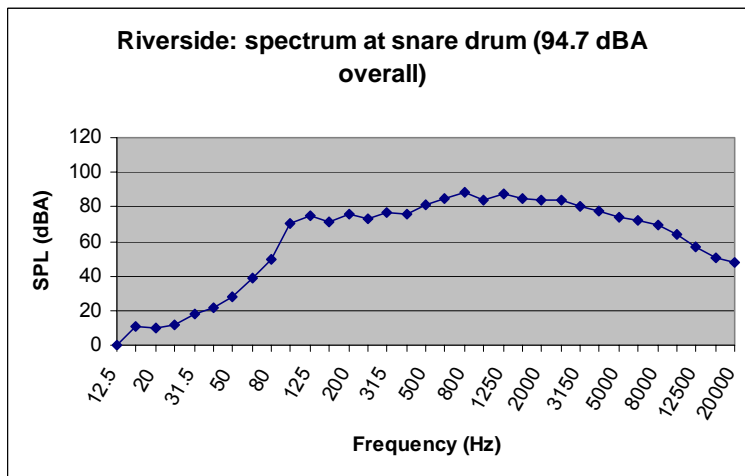
**Figure 37:** Piccolo exposure from marching percussion and click track (10).



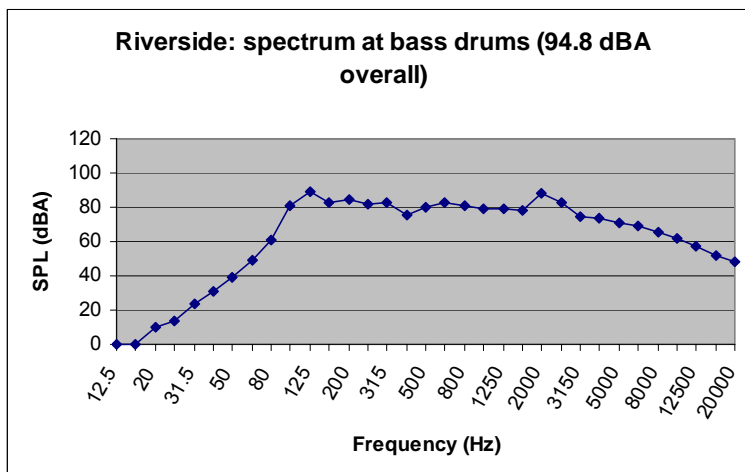
**Figure 38:** Flugelhorn exposure from low brass and alto saxophones.



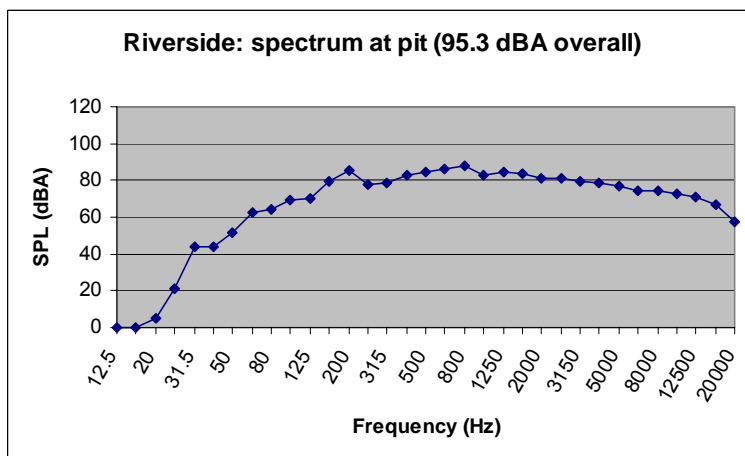
**Figure 39:** Mellophone exposure from low brass and click track (11).



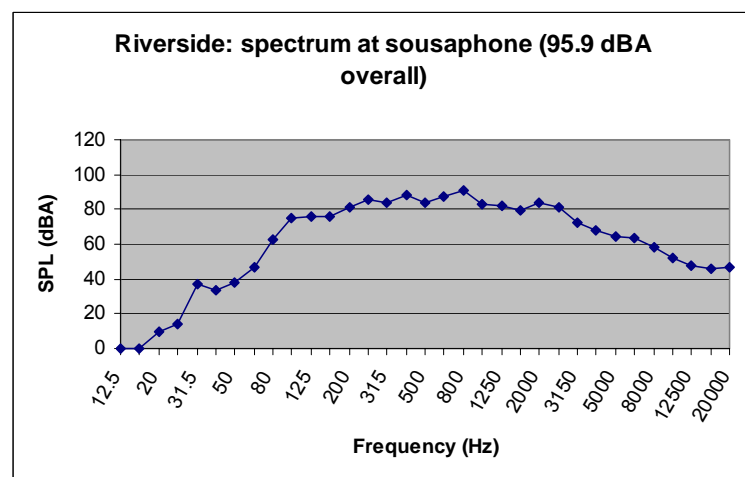
**Figure 40:** Snare drum exposure from marching percussion and click track (4).



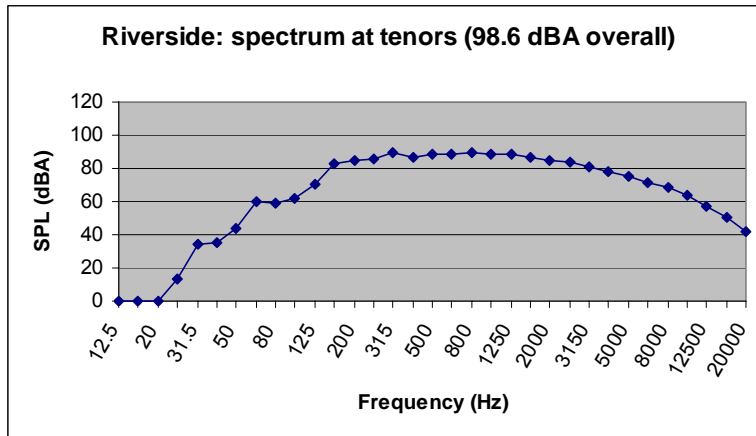
**Figure 41:** Bass drum exposure from marching percussion and click track (5).



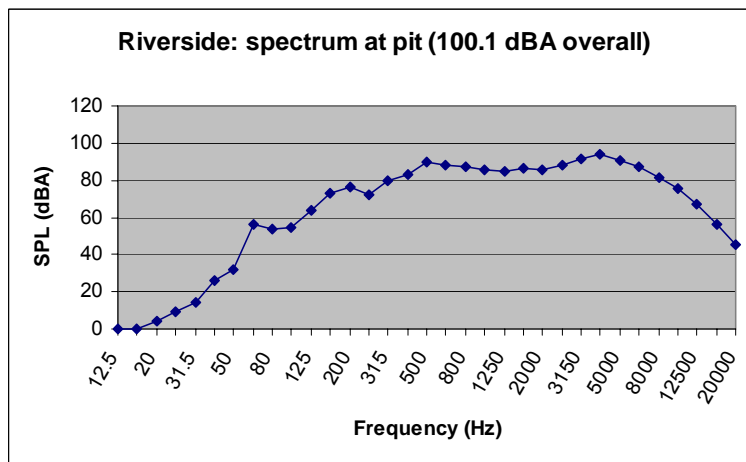
**Figure 42:** Pit exposure from marching percussion.



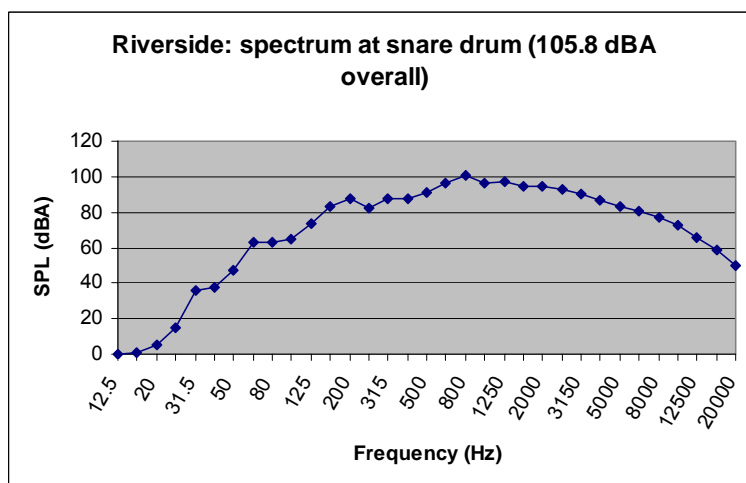
**Figure 43:** Sousaphone exposure from sousaphone, trombones, and click track.



**Figure 44:** Tenors exposure from marching percussion and trumpets.



**Figure 45:** Pit exposure from brass.



**Figure 46:** Snare drum exposure from marching percussion and brass.

The data show that outside rehearsals offer some safety to at least some sections of the Riverside band. In general, woodwinds and trumpets are exposed to safe levels during the length of an outdoor rehearsal. While there are exceptions shown in the data, this trend arises from the fact that woodwinds are usually located to the side or behind the rest of the band in drill forms, and trumpets are usually found very far forward of the rest of the band. Locating the trumpets in front of the rest of the band also has the added benefit of reducing exposure by the trumpets to most of the rest of the band. The Riverside band usually marches with appropriate horn angles (i.e. bells of brass instruments are pointed up to project into a stadium crowd), which further helps to reduce exposure from many instruments by aiming directional frequencies over the head of the person located in front of that instrument.

The data also show that low brass and percussion are generally exposed to dangerous levels during the length of an outdoor rehearsal. Every member of the marching percussion section is exposing himself and all of the other members of the section, and every member of the low brass section is exposing nearby players, which are usually other low brass players. Low brass players tend to be located in the center of drill forms, enveloping them in the sound field of the band.

The click track peaks at 2000-2500 Hz are even more evident for data collected outside than they are for inside data, most likely due to the fact that the speaker must be loud enough to project the clicks across the entire rehearsal field. For unknown reasons the spectrum in figure 32 does not display a click track peak, despite the fact that the researcher's notes indicate it was in use at the time of the measurement. It is possible that the click track either was not in use during this measurement, that the speaker was pointed away from the piccolo, or that the sound was masked by other band members.

It is important to note that these outdoor exposure data are only valid for the 2003-2004 Riverside band, or a band that uses similar relative drill positions. For example, a band that marches trumpets in the back of drill forms and places the drums off to the side all of the time may have widely varying exposure levels compared to the numbers listed above.

## **EXPERIMENTAL RESULTS –PERFORMANCES**

Performances are the culmination of long hours of rehearsal time. The excitement of spectator sports and the desire to perform at the level of rehearsal is strong, and as a result band members can be very excited for performances. A game day performance has two main parts: the field show (the traditional pregame and/or halftime show) and stands music. Stands music is played as a pep band, during the four quarters of a football game. Utmost care was given to creating minimal interference with both bands studied during the collection of the data; as a result, the researcher was unable to take any measurements during field shows. However, measurements of SPLs during stands playing were taken with minimal interference.

### **Performances – Duke**

The Duke football team played 12 games in the 2003 season, 7 of which were at home. Home games involve 2 field shows plus stands music. Half of the band traveled to one away game, half traveled to another, and the full band traveled to a third; away games involve stands music only. A home game involves a very long exposure time; the drumline rehearses for 90 minutes, followed by an hour of full band rehearsal. The band then breaks to get in uniform (approximately 15 minutes) and marches from the practice field to the stadium while the drumline plays. Stands music is played in the stadium, and then after approximately a 15 minute break the band marches a pregame field show. After the pregame show the band immediately begins playing stands music again as the game begins. There is a short period of quiet (approximately 10 minutes) before the halftime field show, then the show is marched and the band plays stands music until the end of the game. Marching percussionists are exposed for at least 6 hours every game day, while the rest of the band is exposed for at least 4.5 hours.

Data collection was only possible for stands music, as game days are very hectic and it was not possible for the researcher to take measurements at pregame rehearsals or while the band was marching to the stadium.

Duke football games are played in Wallace Wade Stadium, a concrete horseshoe-shaped stadium with aluminum bench seating and capacity for 33,941 people<sup>35</sup>. The band is seated centered on a 40-yard line, at the bottom of the stadium. Despite the outdoor location and the lack of any strong reflecting surface forward of or above the band, levels recorded in Wallace Wade are almost as high as in Bone Hall, and exposure times are much longer.

Outdoor performance space (Wallace Wade Stadium)  
 Duke University

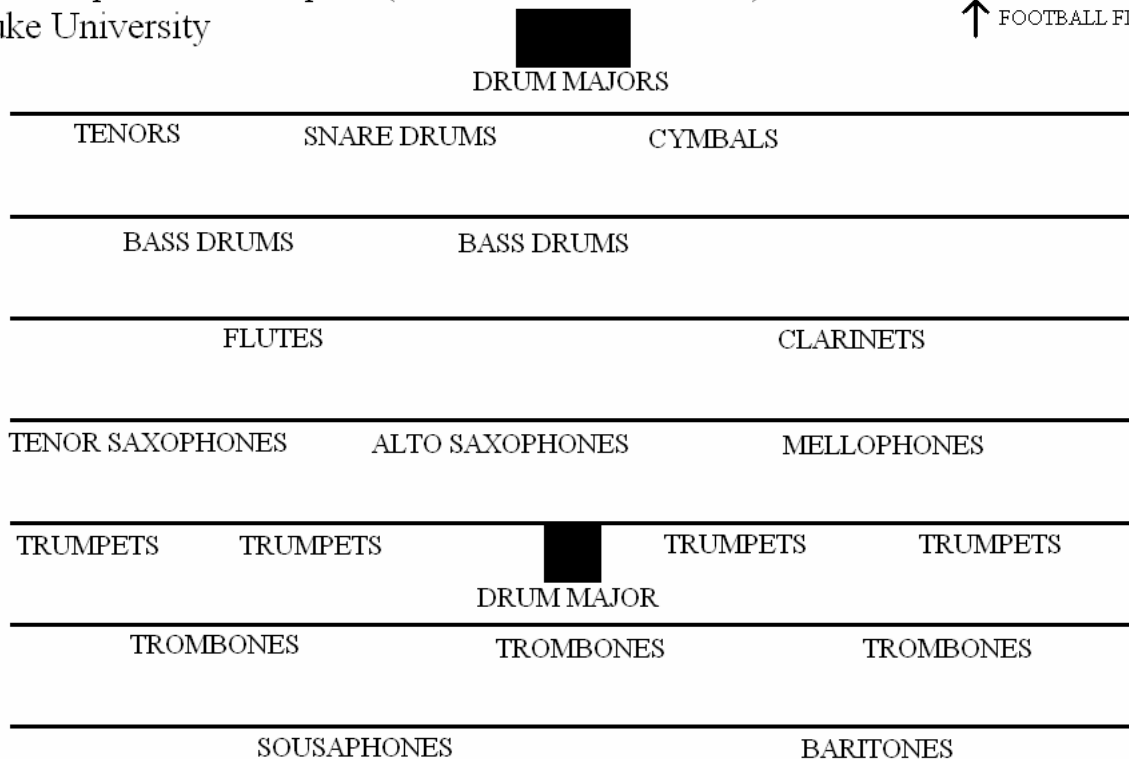
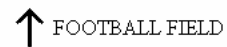


Figure 47: Duke University outdoor performance.

DUKE UNIVERSITY, WALLACE WADE STADIUM				
SPL (dBA)	Location	Principal Sources of Exposure from other instruments	Sample Time	Exposure Time*
98.6	tenor saxophones	trumpets	0:20:42	(2:30:00)
101.2	mellophones	trumpets	0:24:58	(2:30:00)
103.4	bass drums	marching percussion	0:27:56	(2:30:00)
103.5	drum majors (bottom)	marching percussion	0:22:46	(2:30:00)

Table 11: Duke University SPLs for outdoor performances.  
 \*estimated exposure times are in parentheses

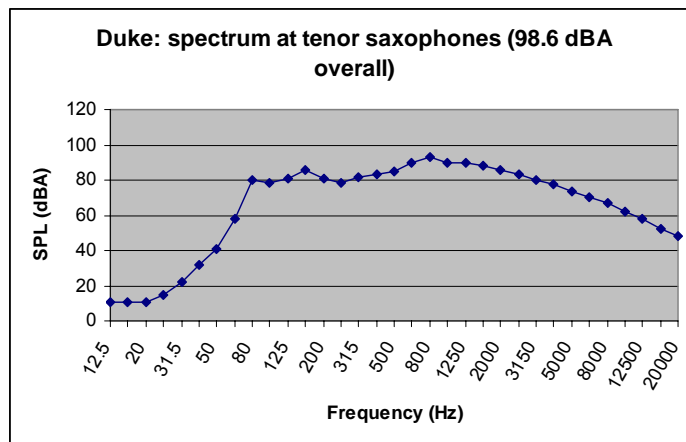
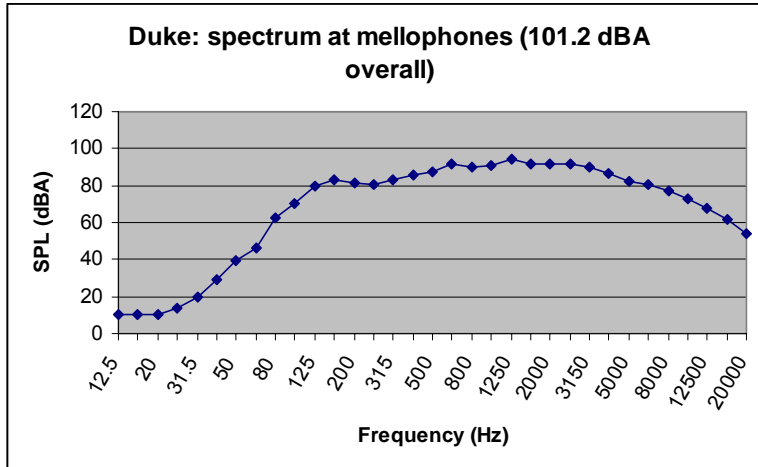
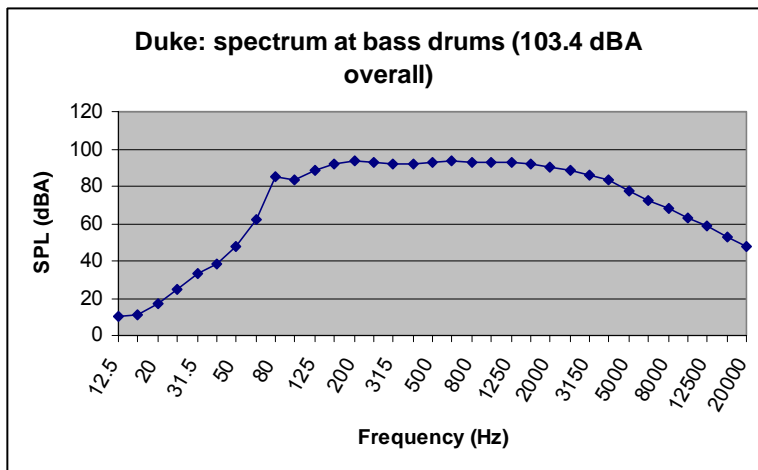


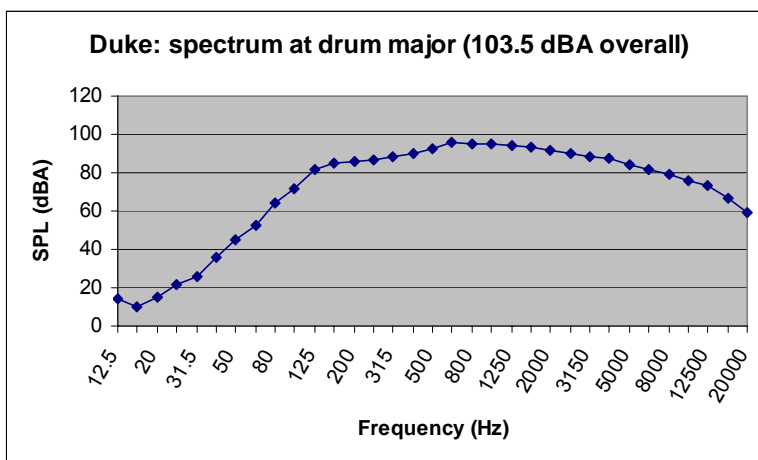
Figure 48: Tenor saxophone exposure from trumpets.



**Figure 49:** Mellophone exposure from trumpets.



**Figure 50:** Bass drum exposure from marching percussion.

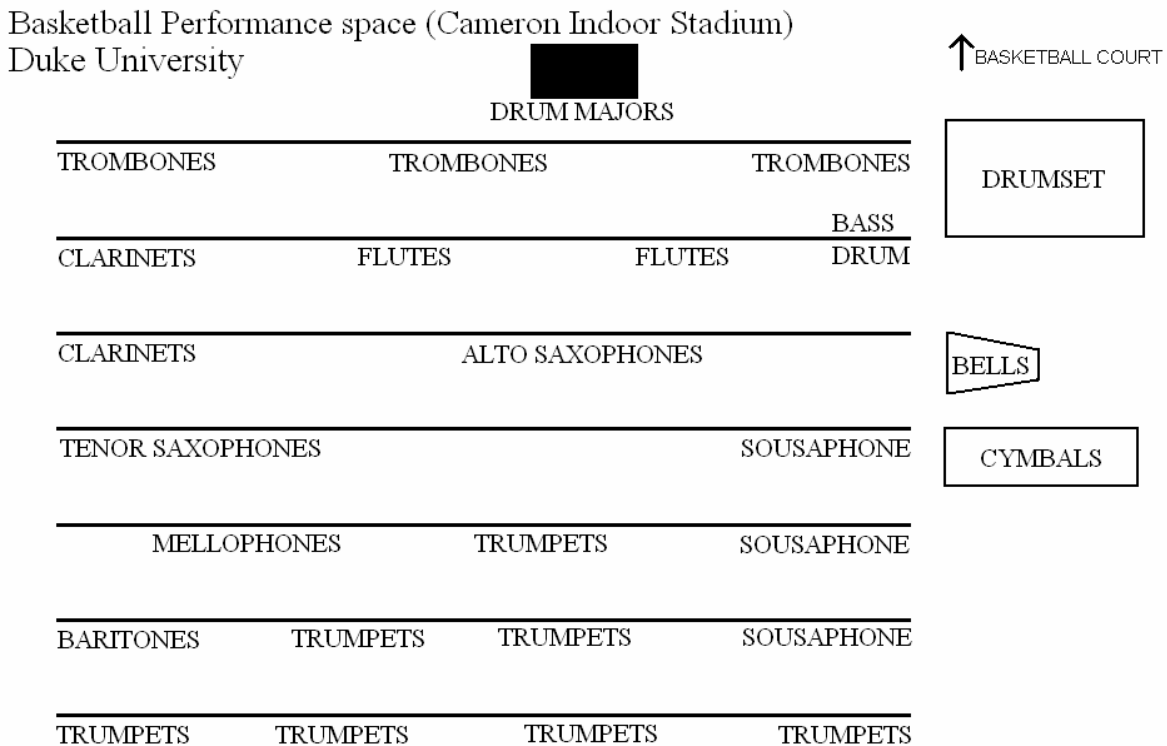


**Figure 51:** Drum major exposure from marching percussion.

The data show that the entire band is exposed to dangerous levels during the course of a football game. This exposure is a result of tens of thousands of loud fans, hard concrete reflective stadium floor, a powerful PA system over which announcements are frequently made, and close proximity within the band. These exposure times do not include pregame rehearsal.

**EXPERIMENTAL RESULTS - BASKETBALL**

At the conclusion of the football season, the Duke band becomes a pep band and entertains the crowd at Cameron Indoor Stadium for Duke Men’s and Women’s Basketball games. Officially, Cameron seats 9,314 in wooden bleachers and plastic folding chairs mounted on concrete and wooden floors (an estimated 11,000 to 11,500 can squeeze in if everyone cooperates). As anyone who has been to a basketball game in Cameron knows, crowd noise can be phenomenal inside the stadium, to the point that it is audible from thousands of feet outside the stadium. Exposure in Cameron is no doubt due in large part to the crowd; the situation would be almost as dangerous if there were no band at basketball games. Additionally, Cameron is a very small stadium compared to the locations at other educational institutions with high-profile NCAA basketball programs, and as a result the band is squeezed into an uncomfortably small space.



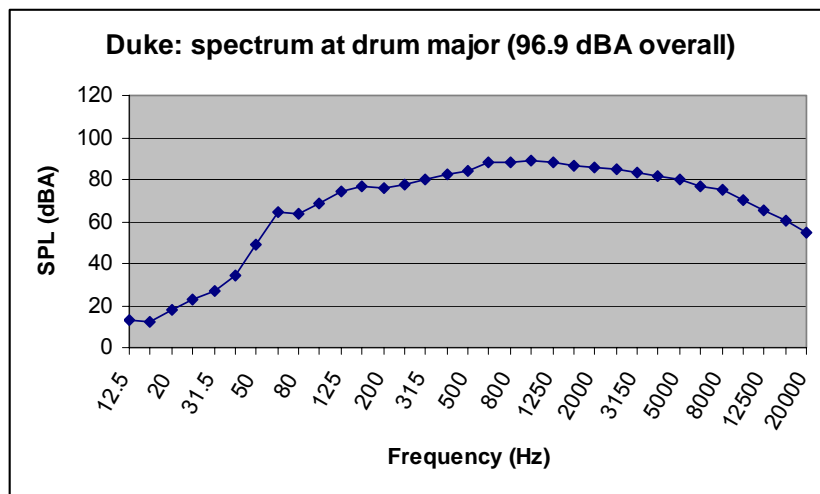
**Figure 52:** Duke University basketball performance.

DUKE UNIVERSITY, CAMERON INDOOR STADIUM <sup>†</sup>				
SPL (dBA)	Location	Principal Sources of Exposure from other instruments	Sample Time	Exposure Time*
96.9	drum major (women's game)	entire band	1:24:04	(4:00:00)
99.5	trombones	clarinets, flutes	0:18:45	(4:00:00)
100.6	sousaphone	sousaphones, trumpets	0:26:45	(4:00:00)
101.1	between bells and drumset	bass drum, cymbals	0:49:36	(4:00:00)
101.2	drum major	entire band	2:23:44	(4:00:00)
101.3	between flutes and clarinets	alto saxophones, trumpets, mellophones	1:06:29	(4:00:00)
102.5	alto saxophones	trumpets	1:25:04	(4:00:00)
102.8	drum major (vs. UNC-CH)	entire band	<b>3:46:08</b>	(4:00:00)

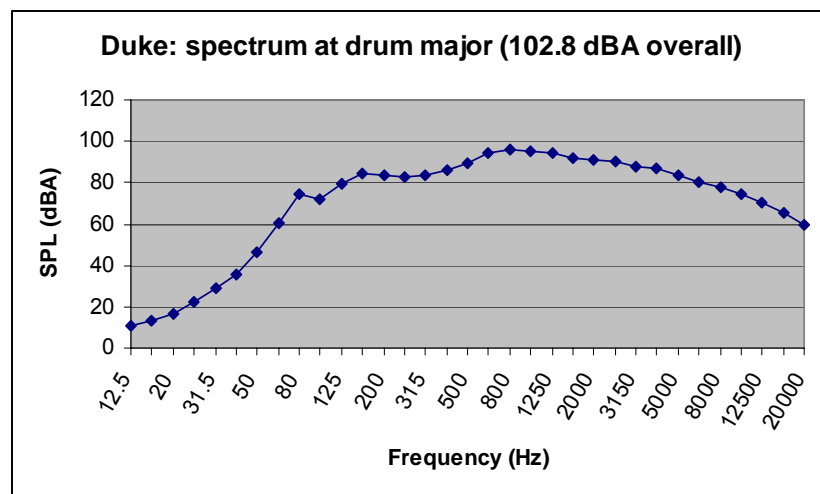
**Table 12:** Duke University SPLs for basketball performances.

\*estimated exposure times are in parentheses

†all measurements taken at men's games unless otherwise noted



**Figure 53:** Drum major exposure from entire band.



**Figure 54:** Drum major exposure from entire band.

Just as in Wallace Wade, exposures in Cameron are dangerous for the entire band. Above are the spectral curves for the minimal and maximal measurements; all curves have similar shapes due to indoor reflection and dispersion. It should be noted that the exposure level is affected by the type of basketball game; women's games have lower levels than men's games, and typical men's games have lower levels than important games such as against the rival team of the University of North Carolina at Chapel Hill.

## **EXPERIMENTAL RESULTS – BONE HALL ACOUSTICS**

### **The Sabine Equation**

Since exposure indoors is largely a function of the room the band rehearses in, the researcher undertook an attempt to determine if acoustical modifications to the room could possibly reduce exposure. Room acoustics are primarily a function of reverberation time ( $T_R$ ), the time required for the sound level to decay by 60 dB. A rough estimate of room's reverberation time can be calculated using the Sabine equation, first used by Wallace Sabine, an architectural acoustics pioneer. The Sabine equation is appropriate when there is a distribution of absorptive and diffusely reflecting surfaces such that the reverberant sound field is the nearly the same everywhere in the room; Bone Hall fits these criteria. Reverberation time is proportional to the ratio of volume to absorption, with the latter expressed as a totally absorptive surface area<sup>36</sup>:

$$T_R = c (V/A)$$

For units of feet, the constant of proportionality  $c$  is 0.049.

### **Duke University – Bone Hall**

Measurements were taken in Bone Hall while a CD of the Duke marching band was played at high volume through powerful speakers. Levels were recorded with the room in its normal configuration for rehearsal (back curtains open [i.e. minimal wall coverage by curtains], standard acoustical material on the walls; condition 1), and then again with the curtains closed [maximum wall coverage by curtains] and additional acoustically absorbent panels placed around the room (condition 2). Reverberation time measurements were also taken for each of these room configurations.

The RT-60 function of the System 824 was used to measure 1/3-octave reverberation times. From the 824 manual:

“The RT-60 analysis display uses the ByTime history to calculate a room decay time. This time is calculated from the cursor position to a point a number of dB down as set by the ‘RT60 dB Down’ setting and then extrapolated to a drop of 60 dB using a ‘Least Squares’ slope calculation method.”<sup>37</sup>

These times were plotted from 315 Hz to 20000 Hz, and a 2<sup>nd</sup>-order polynomial best fit was plotted for each room condition. From each curve the reverberation time at 500 Hz was calculated.

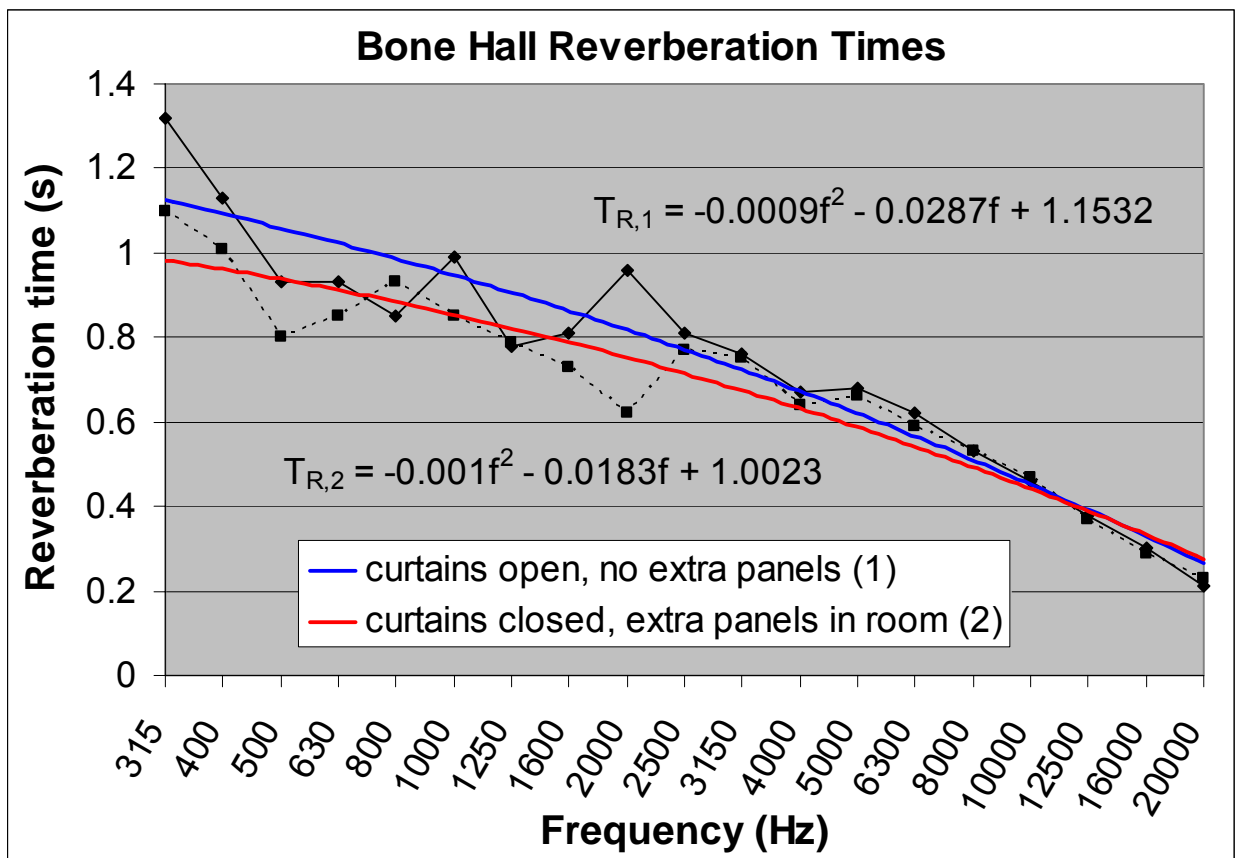


Figure 55: Reverberation times in Bone Hall.

Condition	Calculated reverberation time at 500 Hz (s)	Recorded SPL (dBA)	Theoretical reverberation time	Theoretical SPL
1	1.07	88.2	---	---
2	0.95	87.6	0.99	87.85

Table 13: Bone Hall data.

Bone Hall has an approximate volume of 37,650 ft.<sup>2</sup>. Using the Sabine formula yields 1724 ft.<sup>2</sup> of effective 100% absorptive area in condition 1. The 7 extra panels added to achieve condition 2 are nearly 100% absorbent at frequencies of 500 Hz and above, and have a total area of 143 ft.<sup>2</sup>. When both the effective absorptive area of the room and the area of the panels are added together and used in the Sabine formula, the theoretical reverberation time for condition 2 is 0.99s, which is in good agreement with the calculated result.

Reverberant intensities in a room are inversely proportional to effective absorptive area. Similarly, the change in reverberant intensity is proportional to the ratio of effective absorptive areas ( $R_A$ ). Reverberant intensity level is calculated similarly to SPL:

$$L_{I,R} = 10 \log_{10} R_A$$

For conditions 1 and 2,  $R_A$  is 1.08; the expected change in reverberant intensity, which in this situation is equivalent to the change in SPL, is 0.35 dB, which is on the order of the change measured. Reasons for the difference include the effect of the changing position of the curtains on effective absorptive area and the fact that Bone Hall is not an ideal Sabine room.

Assuming much of the available reflective wall is covered with acoustic paneling (i.e. 10 times the amount of the absorbent area used experimentally), the SPL in Bone Hall will only drop 2.67 dB; despite almost halving the intensity of the reverberant sound, levels are so high that they remain dangerous.

To convey the ineffectiveness of simply adding panels to the room, consider the amount of 100% absorbent area that would be required to reduce a 100 dBA exposure to a safe 85 dBA. The ratio of areas would be 57.67, requiring almost 100,000 ft.<sup>2</sup> of absorbent material. 100,000 ft.<sup>2</sup> is at least **30 times** the wall area of Bone Hall. Of course, this calculation strays well outside the intended uses of the Sabine equation, but it still demonstrates the hopelessness of reducing exposures through simple acoustical modifications.

A 1996 research paper for the Duke course *Acoustics and Music* analyzed the current acoustical situation in Bone Hall.<sup>38</sup> The then-current directors of the symphony orchestra and marching band commented that they felt the room was way too live for ideal rehearsals. Student musicians commented that the room was “muddy” and “sounds terrible.” The only director who expressed appreciation for Bone Hall acoustics was the choral director, who commented that “the

liveness of the hall facilitates rehearsal with [my] group and allows [vocalists] to sing with less effort than they would normally need to exert.” It is clear that both exposure levels and room acoustics would improve with acoustical modifications to Bone Hall, but simple solutions appear ineffective.

## **EXPERIMENTAL RESULTS – PEAK EXPOSURES**

A peak SPL is the maximum instantaneous level that occurs during the period of measurement. Assuming a minimum of one peak for every song or cheer that the band plays, the Duke pep band is exposed to approximately fifty peak events every basketball game. Remember that it is possible that a peak occurs every time a drummer hits a drum, or it is possible that there is only one peak at the loudest point in a song; 50 peaks per game is a best-case (minimum exposure) scenario.

Peaks for normal band playing lie in the 120-125 dBA range. During particularly loud songs played at exciting moments during games, peaks exceed 130 dBA, and maximum peaks approach 140 dBA. At football games, peaks in or near the percussion section exceed 144 dBA. Peaks in the rest of the band lie in the 125-130 dBA range.

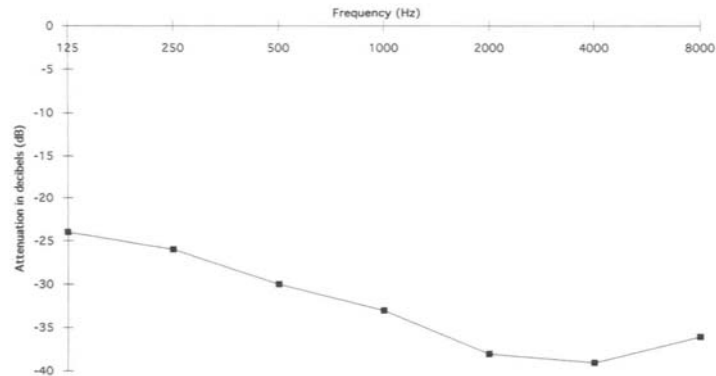
These peaks are all potentially damaging; the 144 dBA peaks are especially frightening because not only are they most certainly doing acute damage every time they occur, they are also in direct violation of the NIOSH recommendations for *non-impulsive* sound.

## **HEARING PROTECTION**

### **Standard Earplugs**

The most common type of earplug is the standard foam earplug, readily available at drug stores and pharmacies. Consisting of pliable foam, it is rolled into a thin cylinder, inserted into the ear canal, and expands to form a sound-attenuating seal. Some industrial earplugs of this type are carefully manufactured and achieve predictable and consistent attenuation of noise if inserted deeply enough. Some of the apparently similar less expensive plugs found in drug stores, however, may offer less consistent degrees of attenuation. While offering considerable reduction of SPL, the main problem with foam earplugs is that they attenuate high-frequency sounds more

than they attenuate low-frequency sounds; their response is not flat. The majority of the greater high-frequency attenuation results from the fact that sounds with a wavelength comparable to the length of the earplug are diffracted away from the earplug instead of continuing uninhibited to the eardrum. Greater high-frequency attenuation also results from the earplug's effect on the main resonance of the ear canal, around 2700 Hz<sup>39</sup>; the earplug changes the ear canal from a semi-closed cylinder to a completely closed cylinder, doubling its lowest resonant frequency.



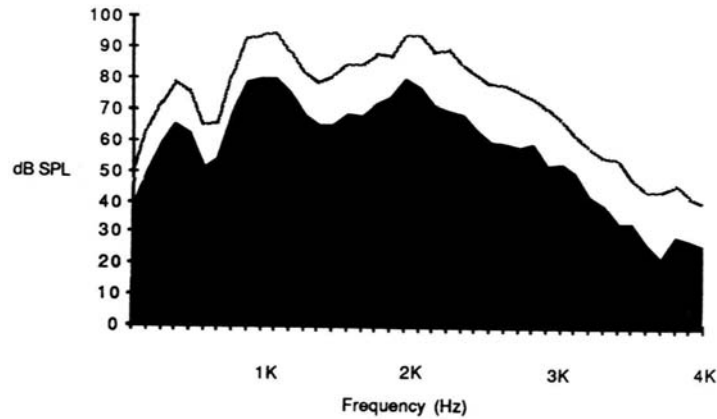
**Figure 56:** Attenuation characteristics of a typical industrial foam earplug that is deeply inserted into the ear canal.<sup>40</sup>

Due to their attenuation characteristics, foam earplugs tend to distort speech to the point that it becomes very difficult to understand, especially in a high-noise environment. Foam earplugs can also lead to physical injury unrelated to hearing. The greater attenuation of high-frequency sounds causes loss of monitoring ability; percussionists lose the ability to monitor the output of high-frequency cymbals and snare, and wind players lose the ability to monitor the high-frequency harmonics of the notes that they are playing. As a result, percussionists tend to strike their instruments more forcefully and wind players tend to overblow to replace lost harmonics; overblowing causes loss of pitch accuracy and poor tone control. These effects can lead to arm and wrist injury and a less musical rehearsal or performance, in addition to increasing noise exposure for other nearby players.

### **Flat-response Earplugs**

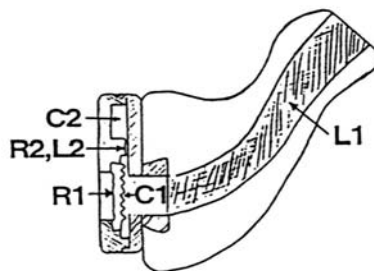
For the student musician exposed to damaging noise levels frequently, ear protection that does not possess a flat response is unacceptable; it could lead to physical injury and distorts sound so much that it becomes unrealistic and is not pleasing. In addition; speech intelligibility

at rehearsals and performances is obviously very important to all musicians, as instructions need to be given and commands must be followed. Etymotic Research, Inc. has produced two flat-response earplugs, the ER-15 and the ER-25, respectively providing 15 and 25 dB of sound attenuation regardless of frequency.



**Figure 57:** The effect of the ER-15 earplug on a violin playing at 440 Hz. The white spectrum in the unattenuated sound level and the black spectrum is the attenuated sound level.<sup>41</sup>

A schematic of the ER-15 is shown below. The ER-15 and -25 earplugs use a small button containing a thin plastic diaphragm and an acoustic resistance (R1 in the schematic). The compliance (C1) of the diaphragm is selected to produce the desired 15 dB of attenuation at low frequencies. At high frequencies, because the normal open ear produces a *boost* of about 15 dB at 2700 Hz, 15 dB of protection at 2700 Hz requires 0 dB of attenuation through the earplug at that frequency. In order to produce that 0 dB of attenuation, the dimensions of the sound channel in the earmold are adjusted so that the acoustic mass (L1) of the air in that channel resonates with the diaphragm compliance and forms a peak at 2700 Hz. Finally, an additional tuned resistive element (R2) is added to smooth the peak. For an ER-25 earplug, the compliance is reduced to increase attenuation and the diaphragm and resistors are adjusted to maintain the shape of the response.<sup>42</sup>



**Figure 58:** The ER-15 earplug; C stands for compliance, R for resistance, and L for inductance.<sup>43</sup>

The ER-15 is appropriate for woodwinds, small strings (violin and viola), nonsolo voice, and all amplified instruments.<sup>44</sup> The ER-25 was designed with percussionists (and the higher sound output they create) in mind; it provides “the correct balance between too little attenuation (with the possibility of an increase in their hearing loss) and too much attenuation (with a loss of monitoring ability).”<sup>45</sup> The researcher wore ER-25s throughout this study.

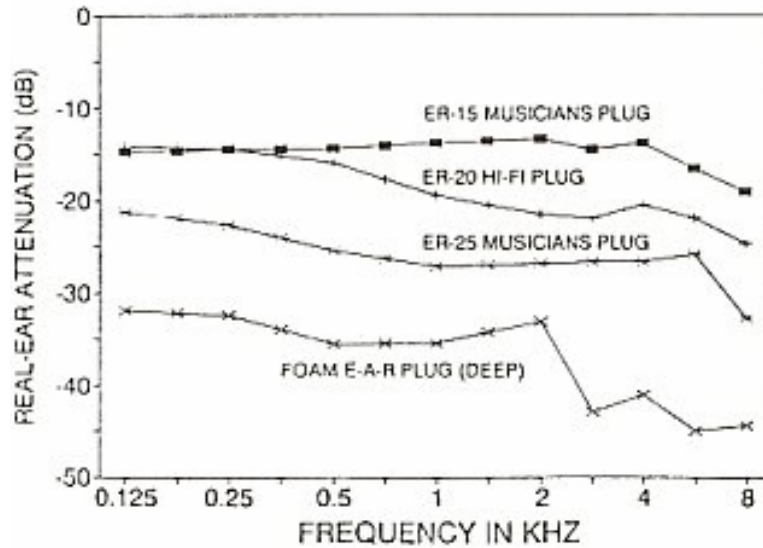


**Figure 59:** A pair of ER-15 / -25 earplugs.<sup>46</sup>

Unfortunately, ER-15 and -25 are rather expensive (between \$125 and \$200, including production and initial fitting of the necessary earmolds), although well worth the one-time cost for any musician who plans to participate in ensembles for a period of years. As an alternative to ER-15 and -25, Etymotic Research also makes an ER-20 plug that retails for less than \$15. This is not a custom plug; it is one size fits most, and is available via the internet and in an increasing number of retail establishments serving musicians. The ER-20 consists of a triple flange design that when fully inserted into the ear canal provides a semi-flat response with 20dB of attenuation. Thus it is neither as flat in response nor nearly as expensive as the ER-15 or -25, but its performance and price make it a candidate for mass purchase for music programs to distribute to participants. Many retailers also offer discounts for bulk purchases of ER-20s.



**Figure 60:** A pair of ER-20 earplugs.<sup>47</sup>



**Figure 61:** Attenuations of ER-15, ER-20, ER-25, and foam earplugs.<sup>48</sup>

### Earplug Drawbacks

Earplugs, even specially designed flat-response plugs, do not reduce sound levels without negative effects. The most noticeable effect is spectrum distortion. Spectrum distortion results from the fact that a loud sound has a different spectrum than a softer sound (usually it involves greater amounts of higher harmonics). Musicians using earplugs will hear a quiet sound, but that quiet sound will have the spectrum characteristic of a loud sound, making it sound slightly unnatural.

Another effect of earplugs is the occlusion effect, where low-frequency energy in the vocal tract (125-150 Hz) is transduced through the cartilaginous portion of the ear canal wall. This means that humming, talking, and breathing cause unpleasant vibrations of the outer canal wall itself. One is not aware of this low-frequency energy when the ear is not occluded because much of the low-frequency energy escapes laterally out of the ear canal.<sup>49</sup> To minimize occlusion, the bore of the earplug should be extended well into the bony portion of the ear canal.

## **HEARING LOSS**

### **Musician's Risks**

This study cannot determine the amount of hearing loss a band member may or may not suffer from as a result of participating in a marching band; this study is only an analysis of risk. Also, individual susceptibility to hearing loss varies according to a number of factors. The first thing a musician who suspects hearing loss should do is visit an audiologist and get an audiogram (a hearing test). This will produce a record of one's current hearing ability. However, audiogram results are much more useful if compared to a reference. The best reference is a previous audiogram of the same musician, so any band director or student musician should have an audiogram performed as soon as possible. Lacking a previous audiogram of the same musician, the current audiogram will be compared to the standard average result according to age and gender. The majority of musicians tested have an audiometric notch in the 3000 to 6000 Hz range<sup>50</sup>; since this notch is prevalent, detecting it is of limited value. However, audiometry can reveal hearing loss occurring faster than normal, abnormal susceptibility to loss, or congenital and/or progressive loss, and as such can lead to further investigation and preventive measures.<sup>51</sup> It is therefore important for musicians to be vigilant in visiting their doctor on a regular basis to make sure that the course of hearing protection they are following is adequate and appropriate.

### **Determining Hearing Loss**

The most common goal of hearing conservation is the preservation of hearing for speech discrimination. Almost all methods of determining hearing impairment use guidelines consistent with this goal. The maximum acceptable hearing loss in any determination of hearing impairment is called the fence, and is usually the average hearing threshold level (HTL) for two, three, or four audiometric frequencies. The fence separates maximum acceptable hearing loss from less severe hearing loss and normal hearing.

Noise regulations attempt to limit excess risk, the difference between the percentage that exceeds the fence in a noise-exposed population and the percentage that exceeds it in an unexposed population. Current regulations refer to the fence as "material hearing impairment".

Material hearing impairment is defined by NIOSH as an average of the HTLs for both ears that exceeds 25 dB at 1000, 2000, 3000, and 4000 Hz (called the 1-2-3-4 kHz definition). Previously the definition did not include measurements at 4000 Hz; however, this frequency is both sensitive to noise and important to the understanding of speech in unfavorable listening conditions; therefore NIOSH has included 4 kHz in their latest definition.

Various other organizations have standards for material hearing impairment and excess risk, including OSHA, the International Standards Organization (ISO), and the Environmental Protection Agency (EPA). These standards differ in the audiometric frequencies used for analysis, linear versus nonlinear effects of noise, the modeling of various age groups, and the modeling of various levels of exposure.

Reporting Organization	Average Daily Exposure (dBA)	Excess Risk %
ISO	90	21
	85	10
	80	0
EPA	90	22
	85	12
	80	5
NIOSH	90	29
	85	15
	80	3

**Table 14:** Estimated excess risk of incurring material hearing impairment (0.5-1-2 kHz definition) as a function of average daily noise exposure over a 40-year working lifetime.<sup>52</sup>

Unlike this study, the excess risks above are calculated by using actual audiometry on workers throughout their careers. While this study cannot confirm that any member of a marching band is losing hearing, statistics show that the risk of loss is very high. The fact that ambient levels during breaks without playing exceed 90 dBA in indoor rehearsals and exceed 87 dBA at halftimes of basketball games is remarkable. Although students clearly do not participate in marching bands for 40 years, the comparison to occupational standards is still valid, because those standards indicate that damage is being done at certain levels, and bands are exposing people to those levels. Actual signs of hearing damage are also reported by students after rehearsals and performances, such as ringing in the ears, muffled hearing (a manifestation of

TTS), and headaches. The estimated 24-hour recovery from the 102-minute exposure to 95 shown in Figure 5 will only take place if the exposed person remains unexposed to high levels for those 24 hours.

### **Further Risk**

Many students who participate in marching bands also tend to participate in other music ensembles. In both high school and college, students in marching bands participate in concert band, jazz band, orchestra, percussion ensemble, pit orchestra, and choir, as well as engaging in individual practice. It is not unreasonable to assume that there is a significant chance that these other ensembles expose student musicians to dangerous levels, although most likely not to the extreme that marching bands do. At the very least, participation in these other ensembles does not allow the periods of quiet that the ears need for rest and recovery from TTS, especially since it is not uncommon for a student musician to be at two or three rehearsals for various ensembles in a single day. In addition, the continued popularity of portable CD and mp3 players allows for the possibility of constant high-level exposure through the use of headphones.

### **RECOMMENDATIONS**

For whatever reason, “political and economic concerns far outweigh those of the health and safety of the instrumentalists and singers.”<sup>53</sup> At the very least, high school music educators should include rudimentary hearing loss education as a part of their ensemble’s instruction. Doing this requires that high school directors be aware of the risks of hearing loss themselves, which is most likely not the case in most situations: “...after years of teaching, the music directors had hearing sensitivities that were 15 dB worse than those who were not subject to noise / music exposure.”<sup>54</sup> This demonstrates that the music educators themselves are suffering from hearing loss and are therefore not aware of the risks involved with lengthy exposure to music.

Music educators should have learned about hearing loss risks in college. Not teaching future music teachers about hearing loss is a great disservice to all future student musicians and is dangerous. Hearing loss education needs to become a standard part of every music education

major across the country if the current trend of increasing hearing loss is to be slowed or reversed.

Students who have not learned about hearing loss through high school must learn about hearing loss in college. While Duke's music program is not designed to train someone for a career of music education, failing to offer even the most basic information about hearing loss to any of Duke's numerous student musicians shows disregard for the health and well-being of the Duke music community and its individual members.

Considering the maximum volume that even low-end computer sound systems are capable of producing and the rise in computer-based music, almost every household in America is a location for potential hearing loss. Students are educated about STDs and pregnancy early in their education so that they may make safe decisions about their life. Not educating students on the risks of hearing loss, while not quite as serious a subject as AIDS and teenage pregnancy, does not allow those students to make educated, safe choices about their hearing.

In general, the vast majority of all involved with marching bands demonstrate zero concern for the well-being of their hearing. Extremely few wear earplugs at rehearsals and performances; in both the Duke and Riverside bands, five or fewer people in each band wore earplugs on a regular basis. Directors not only fail to protect their own hearing, but they fail to educate others about the risk of loss.

All student music programs should provide ER-20 earplugs to their participants free of charge and encourage their use. Information should be distributed about the risks of participating in the band and how hearing protection can drastically lower these risks. In the same way that members of sports teams are required to sign a statement saying that they acknowledge the possibility of injury due to participation, band members should be required to acknowledge the possibility of hearing loss. Using ER-25 earplugs, every single  $L_{eq}$  listed in the data would be attenuated to levels below 85 dBA. ER-20s or -15s would reduce exposure to safe levels for the durations of exposures. Peak levels would be considerably reduced relative to the type of earplug as well.

## **APPENDIX – SYSTEM 824 SETTINGS**

<b><u>Parameter</u></b>	<b><u>Real Time Analyzer Setting</u></b>	<b><u>RT-60 Setting</u></b>
Bandwidth	1/3 Octave	1/3 Octave
Level Weighting	A	A
By-Time Storage	No	Yes
Trigger Signal	N/A	Overall dBA
Arming	Immediate	Immediate
Triggering	Immediate	80 dB Level
Running	Until Manual Stop	3.00 seconds
Measurement Rate	100/second	100/second
RT-60 Calc Range	N/A	20 dB
Auto RT-60 Calc	N/A	Yes

## ACKNOWLEDGEMENTS

Dewey Lawson

Riverside High School Marching Band Members

Ken Davis, Riverside Band Director

Duke University Marching Band Members

Neil Boumpani, Duke Marching Band Director

♪All findings will be presented to the participating band members for their education ♪

## ENDNOTES

- <sup>1</sup> All drill charts courtesy of Riverside High School Band Association, Riverside High School, Durham, NC.
- <sup>2</sup> Kinsler, Lawrence E., et al. Fundamentals of Acoustics. New York: John Wiley & Sons, Inc., 2000. pp. 130-131.
- <sup>3</sup> United States Department of Health and Human Services. National Institute for Occupational Safety and Health. Publication No. 98-126 – Criteria for a Recommended Standard – Occupational Noise Exposure (Revised Criteria 1998). Cincinnati: DHHS, 1998. p. 12.
- <sup>4</sup> Kinsler, p. 130.
- <sup>5</sup> Rossing, Thomas D. The Science of Sound. Reading: Addison-Wesley Publishing Company, Inc., 1990. p. 86.
- <sup>6</sup> Rossing, p. 100.
- <sup>7</sup> “High Fidelity Hearing Protection: Musician’s Earplugs.” Etymotic Research, Inc. Online. 13 April 2004. <<http://www.etymotic.com/ephp/erme.asp>>
- <sup>8</sup> NIOSH, p. 34.
- <sup>9</sup> NIOSH, p. 25.
- <sup>10</sup> NIOSH, p. 26.
- <sup>11</sup> NIOSH, p. 1.
- <sup>12</sup> NIOSH, p. 2.
- <sup>13</sup> NIOSH, p. 17.
- <sup>14</sup> Rossing, pp. 67-68.
- <sup>15</sup> Kryter, Kalr D. The Effects of Noise on Man. New York: Academic Press, Inc., 1970. p. 143.
- <sup>16</sup> Rossing, p. 619-620.
- <sup>17</sup> Rossing, p. 619.

- <sup>18</sup> “Decibel Trivia.” Hearing Awareness and Education for Rockers (H.E.A.R.). Online. 13 April 2004. <[http://www.hearnet.com/at\\_risk/risk\\_trivia.shtml](http://www.hearnet.com/at_risk/risk_trivia.shtml)>.
- <sup>19</sup> Kryter, p. 186.
- <sup>20</sup> Berglund, Birgitta, ed. and Thomas Lindvall, eds. Community Noise. Stockholm: Center for Sensory Research, 1995. p. 56. <<http://www.nonoise.org/library/whonoise/whonoise.htm>>.
- <sup>21</sup> Kryter, p. 144.
- <sup>22</sup> Berglund, p. 53.
- <sup>23</sup> Berglund, p. 56.
- <sup>24</sup> Kryter, p. 140.
- <sup>25</sup> Kryter, p. 192.
- <sup>26</sup> Kryter, p. 192.
- <sup>27</sup> Kryter, p. 192.
- <sup>28</sup> Rossing p. 616.
- <sup>29</sup> Rossing, p. 616.
- <sup>30</sup> Rossing, p. 617.
- <sup>31</sup> Rossing p. 617.
- <sup>32</sup> Rossing p. 617.
- <sup>33</sup> System 824 Reference Manual, Revision G. 2003. p. 389
- <sup>34</sup> Walker, R. Blueprints for Duke University’s Biddle Music Building Bone Hall Renovations. 24 June 1994.
- <sup>35</sup> “Wallace Wade Stadium.” GoDuke.com. Online. 16 April 2004. <<http://goduke.collegesports.com/sports/m-footbl/spec-rel/010703aaa.html>>.
- <sup>36</sup> Rossing, p. 465.
- <sup>37</sup> System 824 Reference Manual, p. 347
- <sup>38</sup> Martel, Nicole L. “An Acoustical Analysis of Duke University’s Bone Hall.” 23 April 1996. pps. 20-22.

- <sup>39</sup> Chasin, Marshall. Musicians and the Prevention of Hearing Loss. San Diego: Singular Publishing Group, Inc., 1996. p. 86.
- <sup>40</sup> Chasin, p. 86.
- <sup>41</sup> Chasin, p. 88.
- <sup>42</sup> Beck, Douglas L. Interview with Mead Killion, Ph.D., Founder of Etymotic. 18 August 2003. Online. 16 April 2004.  
<<http://www.audiologyonline.com/interview/displayarchives.asp?ID=215>>.
- <sup>43</sup> Chasin, p. 89.
- <sup>44</sup> Chasin, p. 93.
- <sup>45</sup> Chasin, p. 94.
- <sup>46</sup> “Earplugs – ER9 – ER15 – ER25.” Online. 14 April 2004.  
<<http://www.ultimateears.com/earplugs.htm>>.
- <sup>47</sup> “Cabot ER20 EAR HiFi Ear Plugs.” zZounds.com. Online. 12 April 2004.  
<<http://www.zzounds.com/item--CABER20>>.
- <sup>48</sup> “High Fidelity Earplugs.” Otarion Hearing Aid Centre. Online. 14 April 2004.  
<<http://www.auracom.com/otarion/earplugs.html>>.
- <sup>49</sup> Chasin, p. 113.
- <sup>50</sup> Chasin, p. 17.
- <sup>51</sup> Chasin, p. 106.
- <sup>52</sup> NIOSH, p.20.
- <sup>53</sup> Chasin, p.151.
- <sup>54</sup> Chasin, p. 35.