

Measurement of Background Noise, Signal to Noise Ratio, and Reverberation Time in Classrooms

A student contest sponsored by the
National Society of Black Physicists
and the
Acoustical Society of America

Summary

One critical application of acoustics is in classroom design (Seep *et al.*, 2000). The key physical metrics in classroom acoustics, background noise, signal to noise ratio, and reverberation time, can affect speaker intelligibility, mood, student concentration and overall learning (Nelson *et al.*, 2002). As a result in many jurisdictions there are standards that set limits for these key metrics (Evans, 2005).

Background noise, signal to noise ratio, and reverberation time can be easily measured with inexpensive (\$50 or less) equipment and/or software. The simplicity of these measurements, the social relevance of the science, and our desire to have students explore all areas of physics have encouraged the National Society of Black Physicists and the Acoustical Society of America to co-sponsor a student poster contest for the 2008 NSBP/NSHP conference. Students working either alone or in groups can conduct a study and present their results in a poster at the conference in February 2008.

The contest prize includes a \$500 cash prize and a free membership in the Acoustical Society of America.

Introduction

Acoustics is a branch of physics concerned with the study of sound (mechanical waves in gases, liquids, and solids). It is a rich field with multiple branches including aeroacoustics, architectural acoustics, bioacoustics, medical acoustics, musical acoustics, physical acoustics, psychoacoustics, seismology, underwater acoustics and several others (_____, 2007). Because mechanical waves are so ubiquitous, acoustics is by nature an inter-disciplinary field, drawing people from widely differing backgrounds. But any scientist that studies acoustics is called an acoustician.

A full acoustics course is not commonly offered in the usual undergraduate physics curriculum. Acoustics is covered in most general physics textbooks, but often the topic is presented at the end of the semester of the introductory mechanics course, *i.e.*, general physics I, and not picked up again explicitly elsewhere in the standard physics curriculum (Rossing, 2002). Yet there are many jobs and long term career prospects for physicists in acoustics (Hansen, 2004). In a recent article Busch-Vishniac and West highlighted some of the rich applications of acoustics, and how to attract more students to the field. (Busch-Vishniac and West, 2007).

One critical application of acoustics is in classroom design (Seep *et al.*, 2000). Much research in the fields of education, psychology, audiology, and engineering has been applied to classroom acoustics (Hodgson, 1988; Serra and Biassoni, 1998; Hodgson *et al.*, 1999; Bistafa and Bradley, 2000; Haines *et al.*, 2001; Hodgson and Nosal, 2002; Lundquist *et al.*, 2003; Shield and Dockrell, 2003). The key physical metrics

in classroom acoustics, background noise, signal to noise ratio, and reverberation time can affect speaker intelligibility, mood, student concentration and overall learning (Abimbade, 1999; Hodgson, 1999; Hodgson *et al.*, 1999; Polich and Segovia, 1999; Bradley and Lang, 2000; Crandell and Smaldino, 2000; Nelson, 2000; Nelson and Soli, 2000; Siebein *et al.*, 2000; Hodgson, 2002; Hodgson and Nosal, 2002; Nelson *et al.*, 2002; Godfrey, 2003; Shield and Dockrell, 2003; Skarlatos and Manatakis, 2003; Dockrell and Shield, 2004; Dockrell *et al.*, 2004; Hodgson, 2004; Siebein, 2004; Beaman, 2005; Choi and McPherson, 2005; Dreossi and Momensohn-Santos, 2005; Sato *et al.*, 2005; Kennedy *et al.*, 2006; Dockrell and Shield, 2006). As a result, in many jurisdictions there are standards for the maximum background sound level, minimum signal to noise ratio, and maximum reverberation times in classrooms (Lubman, 1997; Malakootian, 2001; Sutherland and Lubman, 2004; Evans, 2005; Kobayashi *et al.*, 2007).

While requiring some specific training to fully understand all the physical concepts, these metrics can easily be measured by any undergraduate physics major (Rossing, 1986; Hansen and Rossing, 1999; Hodgson *et al.*, 1999; Rossing and Hansen, 2001; Knecht *et al.*, 2002; Crandell *et al.*, 2004b; Hansen, 2006). Indeed Busch-Vishniac and West mention how a high school student working at Johns Hopkins surveyed a number of classrooms to see if they met the standard of 35 dB(A) for background noise. This simple study apparently had a large impact on the campus. Apparently there tended to be a large spike in energy in the 16 kHz octave band¹. After some work with the facilities managers, they discovered that the motion detectors were emitting noise in that band. Although the instructors and facilities managers could not hear the high-pitched tone, owing perhaps to changes in hearing with age, many of the students could, and found it irritating. As a result of this work, the construction contracts at Johns Hopkins have been changed to include acoustical requirements.

The simplicity of these measurements, the social relevance of the science, and our desire to have students explore all areas of physics have encouraged the National Society of Black Physicists and the Acoustical Society of America to co-sponsor a student poster contest for the 2008 NSBP/NSHP conference. Students, working both alone or in groups, can conduct a study and present their results in a poster at the conference. Posters will be judged on the students' ability to converse with the judges and show insight into the physics of the problem, indications of careful work (calibration, experimental methodology and analysis), and if they put in extra work above and beyond measurements in a single location, *i.e.*, did they do the measurements in libraries, dorm rooms, local K-12 schools, with and without various absorbers in the rooms, etc.

Acoustics Background

Here we will only highlight some of the key concepts for this exercise. For a quick introduction to acoustics refer to any general physics textbook and either of the commonly used acoustics textbooks (Giancoli and Gahala, 2000; Kinser *et al.*, 2000; Rossing, 2001; Long *et al.*, 2005; Raichel, 2006; Egan, 2007).

Sound is what we call our perception of waves emanating from some mechanical vibration. Being a wave, sound can be characterized by its amplitude, frequency and speed. Mechanical vibrations, thus sound sources, are ubiquitous, and exist in all frequency ranges. In any given space and at any given

¹ Octave bands are convenient ways to divide the frequency spectrum into intervals. In acoustics the octave is the interval between two frequencies which are in the ratio of $10^{0.3}$ to 1. (This is different from the definition used in music.) The 16 kHz octave band has a lower limit of 11.2 kHz and an upper limit of 22.8 kHz.

time, the total sound field will contain waves at any number of frequencies and at various intensities. Some of the waves will be detected by human ears, while different sensors will be needed to detect other waves.

The *loudness* of sound is related to the amplitude of the wave, which is also related to the energy of the wave. Loudness is also related to *intensity*, a measurable quantity, and also to *sound pressure level* (SPL), also a measurable quantity. These quantities are stated in units of *decibels* (dB). If the intensity of sound at some location \mathbf{r} , at some time t , and at some frequency f is I , and some reference intensity is I_0 , the

decibel level is defined as $10 \log\left(\frac{I}{I_0}\right)$. If loudness is measured in terms of sound pressure level, the

expression for decibel is $20 \log\left(\frac{P}{P_0}\right)$, where $I = \frac{P^2}{\rho c}$, ρ is the medium density, and c is the speed of

sound.

In the normal classroom environment the sound field would consist of the main speaker plus any sounds that may exist in the background. Sound that is normally not intended to be present, not needed, or somehow is not normally monitored is called noise. Noise in the classroom can degrade the quality of the educational experience. Examples of background noises include environmental sounds such as wind and traffic noise, cell phone ringers, alarms and beepers, people talking, various bioacoustical noises, and mechanical noise from devices such as conditioning, fans and blowers, power supplies and motors.

Until very recently classroom acoustics standards in the United States had not yet been formalized (Lubman, 1997). In 1995 the American Speech-Language-Hearing Association recommended that unoccupied classrooms noise levels, averaged over all frequencies in the human audibility range (20 – 20,000 Hz), not exceed 30 dB. In 2002 American National Standards Institute adopted 35 dB as the maximum background noise (Sutherland and Lubman, 2004). In Sweden the standard is also 35 dB (Evans, 2005).

The standard also requires that the signal to noise ratio in a classroom be +15 dB. The signal level is of course related to the room's amplification scheme, if any. But classrooms that maintain a background noise level below 35 dB will allow speakers' voices to reach all listeners at the desired +15 dB signal to noise ratio (Nelson *et al.*, 2002).

Acoustic reverberation is the persistence of sound energy in an enclosed space due to reflections from space boundaries and other surfaces. When sound is produced in a space with reflecting surfaces, a large number of echoes build up and then slowly decay as the sound is also absorbed by the walls, air and other contents in the room. Listening to echoes is a very well known phenomenon even in outdoor areas; all that is needed is some kind of sound reflection surface. But in an enclosed space, especially a classroom, reverberation can seriously diminish the intelligibility of intended communication.

Reverberation time is a measure of the sound energy decay. It depends upon sound absorption at the boundaries and interior surfaces and properties of the air in between, *i.e.*, temperature. Long reverberation times indicate strong echoes. In a classroom with long reverberation times students will perceive words as overlapping, and words like "cat", "cab", and "cap" may all sound very similar. If on

the other hand the reverberation time is too short, tonal balance and loudness may suffer (Wikipedia contributors, 2007).

In the late 19th century Sabine developed an empirical relationship between reverberation time in a room, its sized and the nature of the absorption. He determined that the reverberation time T is directly proportional to the room volume V and indirectly proportional to the absorption surface area A , *i.e.*, $T \propto \frac{V}{A}$. Sabine assumed that acoustic waves propagate along a ray from a point source, and are both absorbed and reflected by surfaces. In a predominately reflecting space, after a large number of reflections, the volume will be filled with sound energy such that the energy density is the same in all directions.

Solving the differential equation for energy density as a function of time lead to the familiar exponential decay formula, $\mathbf{E} = \mathbf{E}_0 e^{-t/\tau}$, where τ is a characteristic time that depends on the volume of the room, the absorptivity of the boundaries, and the speed of sound c , $\tau = \frac{4V}{Ac}$. Converting the sound energy density to sound pressure level (SPL), and taking the log of this equation results in an equation relating decibels as a linear function of time. Defining the reverberation time as the time required for the level to decay by 60 dB below that of the source results in the Sabine reverberation formula.

$$\mathbf{T} = \frac{0.161V}{A} \text{ (metric) or } \mathbf{T} = \frac{0.049V}{A} \text{ (English units).}$$

Experimentally reverberation time can be measured by introducing some impulse noise and recording the sound level. From there the data can be analyzed to against this simple model.

Alternatives to this simplified model include more complex situations of non-rectilinear shaped spaces, the existence of standing waves, and the spatial distribution of absorptivities (António *et al.*, 2002; Kostek and Neubauer, 2002; Stauskis, 2003; Nosal *et al.*, 2004; Wang *et al.*, 2005).

Key things to note are that reverberation time may be frequency dependent, *i.e.*, sound at one frequency may be easily absorbed while others more reflected. Additionally the geometry of the enclosure may allow for standing waves.

Experimental Methods

The objective of this exercise is to measure and analyze the key metrics for classroom acoustics. All of these measurements can easily be measured using a computer with a well calibrated microphone, or with a more specialized sound level meter. In the appendices here we demonstrate recording and analysis protocols using readily available tools, but there are many other low to no-cost tools available to do the recordings and analyses (Plichta, 2005; McGuire *et al.*, 2006).

To complete these experiments you will need a sound level meter², a computer with a sound card and speakers, a signal generator that can produce a 1000 Hz pure tone, a well-calibrated microphone,

² **Using a sound level meter.** Sound level meters usually read on two different dB scales, dB(A) and dB(C). Sound fields contain a mixture of frequencies and these two scales are different ways of

software that facilitates recording and saving files in the wav format, and software to do the analysis, *e.g.*, Mathematica (Sparrow and Russell, 1998).

Calibration

When comparing sound intensities from different sources, using different equipment and perhaps different procedures, it is important to at least have a common calibration procedure. We shall describe here the calibration procedure of Asplund for this project (Asplund, 2002). Inasmuch as possible this calibration should be made in an acoustically isolated (anechoic) space. Measurement of sound intensity can be made by placing a sound level meter or microphone at a specified distance from the sound source, *e.g.*, and converting the microphone signal from voltages to a dB level (Winholtz and Titze, 1997; Angerstein and Neuschaefer-Rube; Rantala *et al.*, 2002; Stone *et al.*, 2003; Crandell *et al.*, 2004b).

The calibration equipment consists of a white noise source that can produce filtered noise at $1000 \text{ Hz} \pm 250 \text{ Hz}$, 18 dB/octave, a loudspeaker connected to the white noise generator, a sound level meter, a computer microphone, a digital signal generator that can produce a 1000 Hz pure tone and a switch between the microphone output and the pure tone signal generator output. All of these components are commercially available, and indeed are generally available in the common equipment inventory of a physics department. Wav files of white noise and pure tones are available on the internet. These files can be played on a normal computer with reasonable speakers, but of course more responsive speakers with less distortion would be preferable. While a pure tone from the same computer speakers is possible, the idea is to have a separate, but certain, input source in order to make comparisons.

Figures 1 and 2 show how the equipment should be arranged. The microphone and the sound pressure meter should be 15cm from the front face of the speaker, and arranged at the speaker's midline inasmuch as possible. This arrangement, essentially measuring the sound by two methods, will allow for the association of a specific sound intensity level with an output voltage from the microphone.

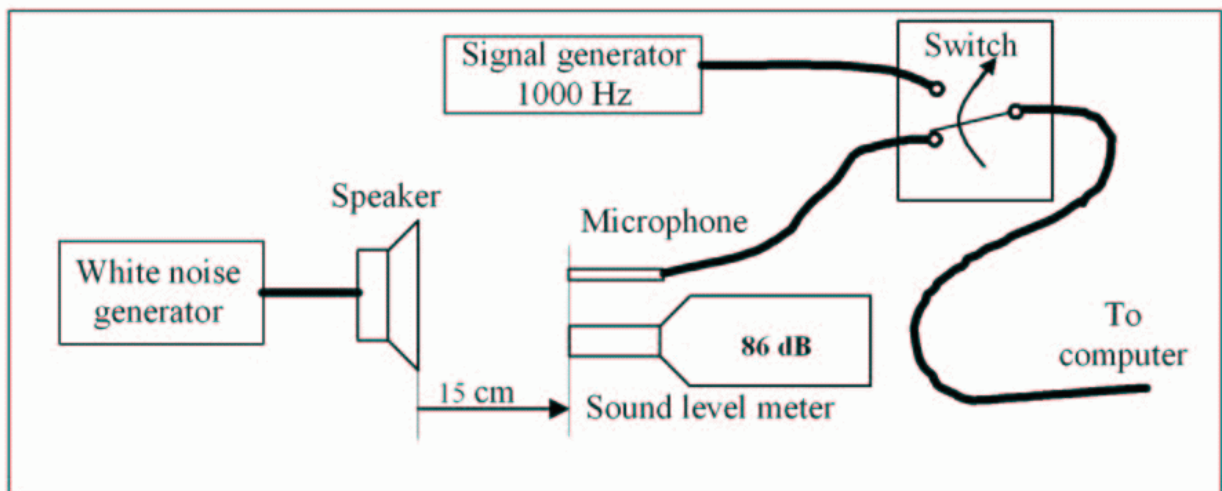


Figure 1. Schematic diagram of components' setup. From Asplund, 2002

averaging over the frequencies. Sound level meters also have two different time scales for collecting successive data points. For this work always use the slow scale

The white noise generator is set so that the sound from its speaker is filtered noise at 1000 Hz (\pm 250 Hz 18 dB/octave). The sound level meter should be set on the dB(A) and slow scales. The sound level from the loudspeaker of the white noise generator is adjusted so that the sound level meter records a level of 86 dB. At the same time the signal from the microphone cable is measured using a millivolt meter or a computer with a program that measures dB. The input level should be adjusted so that it registers an average of 86 dB. Then the input to the computer is switched from the microphone output to the 1000 Hz sine wave signal from the tone generator. The level of the tone generator is then adjusted so that it also records 86 dB in the computer program. The microphone signal has now been calibrated and matched to the level of the 1000 Hz signal from the pure tone generator. All systems that have been calibrated in this way will have microphone signal levels (in millivolts) that are the same for the same sound intensity levels.

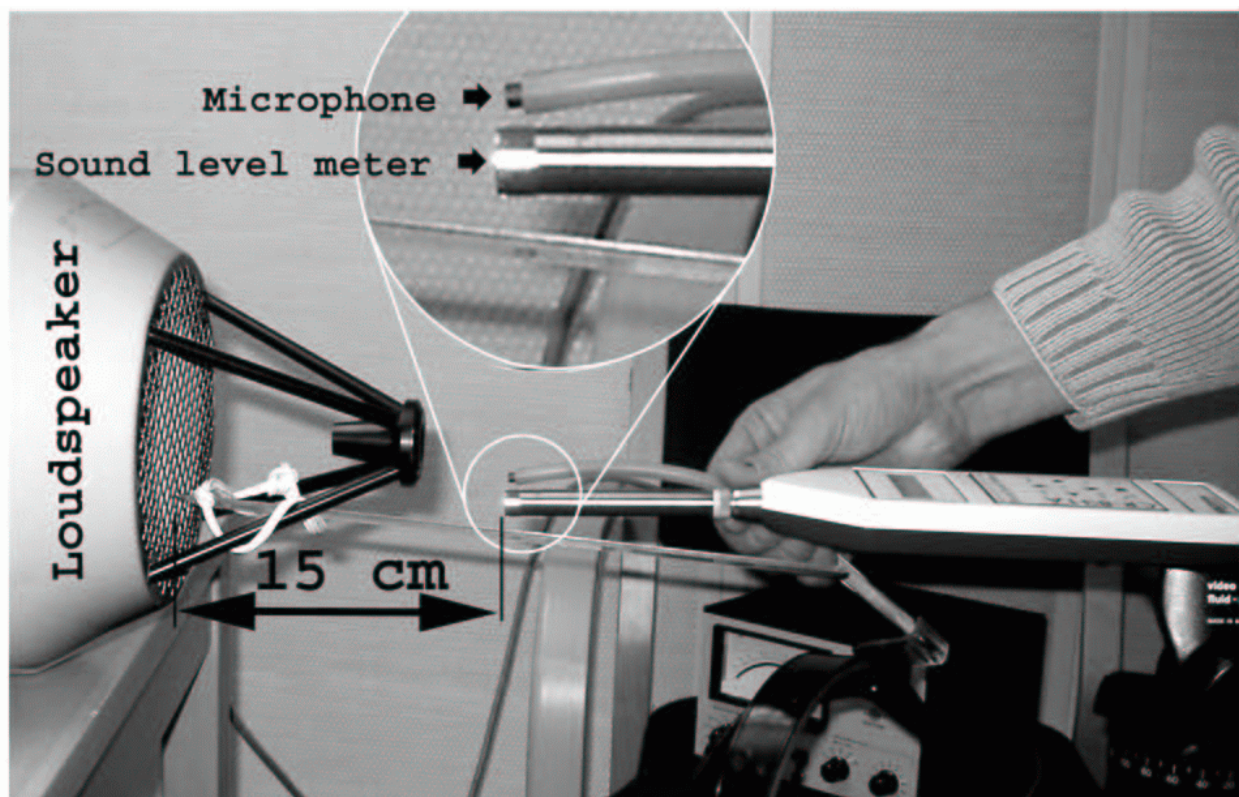


Figure 2. Photograph showing how the components are assembled. From Asplund, 2002

Non-acoustical measurements

For each tested classroom its dimensions and absorption surface area should be measured. Then its volume, and the possibility of standing waves should be determined (Kinser *et al.*, 2000).

Crandall has proposed internal and external variables for characterizing acoustics in enclosed spaces (Crandell and Bess, 1992; Crandell and Smaldino, 1996; Crandell, 1998; Crandell and Smaldino, 2000; Crandell *et al.*, 2004a; Crandell *et al.*, 2004b; Smaldino and Crandell, 2004). Knecht, *et al.*, found that overall Crandall's 1995 general checklist may not be predictive of the key classroom acoustics, though some variables may be more predictive than others (Knecht *et al.*, 2002).

Measuring background noise

In an empty classroom, the situation used to determine compliance with the standards, background noise measurements should be made at a half dozen or so different locations using either the sound level meter, a computer and microphone, or preferably both. Nodes of any possible standing waves should be avoided. When the measurements are made via microphone and computer the resulting wav file can be decomposed into frequency components where features such as in the Johns Hopkins case can be revealed. The measurement times should be long enough to get a representative sample, but obviously not so long as to make the amount of data unmanageable, or to capture aperiodic and rare events. A report on these measurements should include the average intensity over all frequencies, as well as intensities at specific frequencies of particular interest, *e.g.*, 2-4 kHz.

Measuring signal to noise ratio follows quite naturally from background noise measurements. Here some target signal, in this case the main speaker's voice while speaking normally perhaps with some amplification, is measured. From those measurements the background noise level is subtracted. To be within standards the result should be no less than 15 dB. Note that the classroom standard for signal to noise ratio applies to all speakers at all positions in the room. That is, it applies not only to the main speaker at the front of the room, but to a speaker who may be seated anywhere in the audience and is perhaps asking a question.

Measuring reverberation

Using the same equipment, an impulse sound is introduced by crashing together two wooden blocks, firing a starter pistol, popping a balloon, or by some other suitable method (Davies *et al.*, 1981; Marshall, 1990; Jing and Fung, 2006). The impulse noise should be louder than 60 dB. As the impulse sound is made, the resulting transient sound intensity is recorded and analyzed. Data in a wav file can be loaded into Mathematica where it can be manipulated to determine the reverberation time (see Appendix 2). Alternatively there are many inexpensive software packages that can make the recordings and give you the reverberation time directly.

Reporting the data

Data reports and poster presentations should include descriptions of the classrooms, *i.e.*, size, position of windows, doors, and air vents, presence of carpeting and furniture, whether or not the HVAC system was working during the measurements and other relevant factors. It would be advantageous to show a diagram showing the location of the microphone (or sound level meter) for each recording. On the signal to noise measurements the target signal should correspond to the common spoken voice (Hodgson *et al.*, 1999; Nelson *et al.*, 2002).

Again posters will be judged on the students' ability to converse with the judges and show insight into the physics of the problem, indications of careful work (calibration, experimental methodology and analysis), and if they put in extra work above and beyond measurements in a single location, *i.e.*, did they do the measurements in libraries, dorm rooms, local K-12 schools, with and without various absorbers in the rooms, etc.

All participants should maintain an experimental log book and all wav files. The wav files will be combined into a national dataset on classroom acoustics for later analysis. NSBP will set up an e-forum and blog space for this contest. See the NSBP website, www.nsbp.org, for the latest updates.

Appendix 1. Recording and Analyzing Sounds Using WavePad©

Rebecca Carr (Acoustics Technician)
United States Naval Academy
Physics Department
11 October 2007

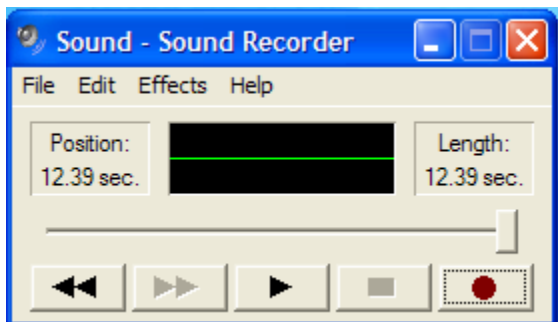
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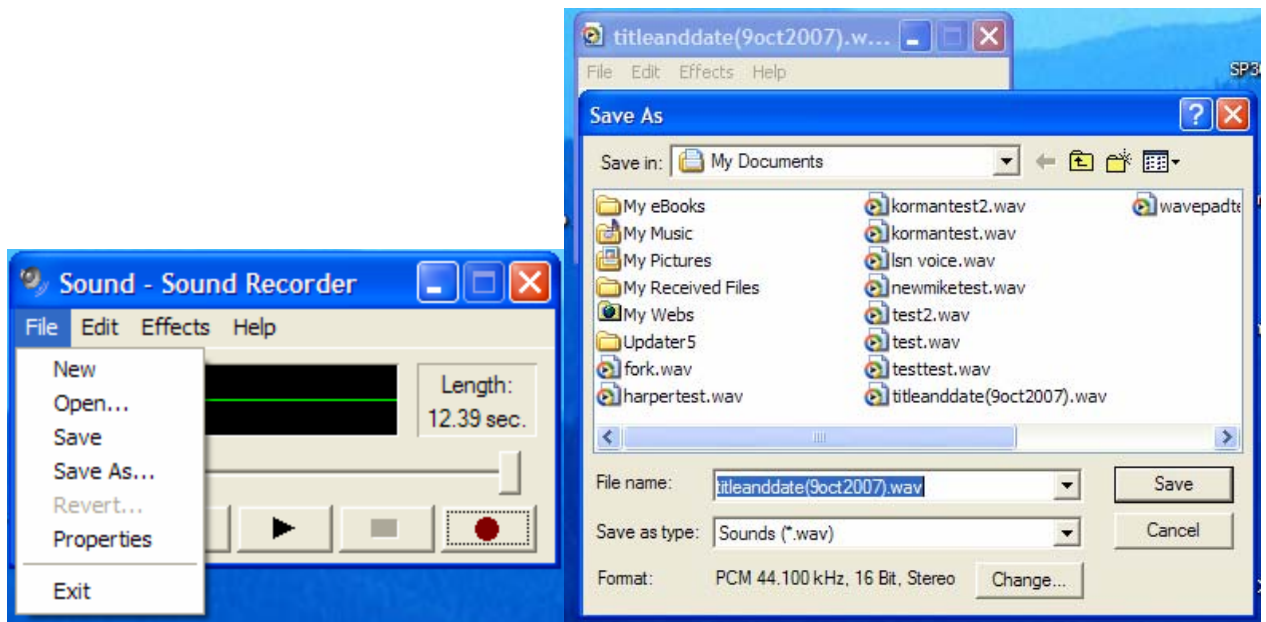
WavePad© is one of the many software packages freely available on the internet for recording sound fields and saving them to a computer. Some of these packages have rather extensive analysis suites as well. Microsoft Windows has an onboard sound recorder. Here we describe how to record and save a wav file using WavePad© and the onboard recorder in Windows.

- A. Recording Sound in *Sound Recorder* and Uploading It into WavePad©

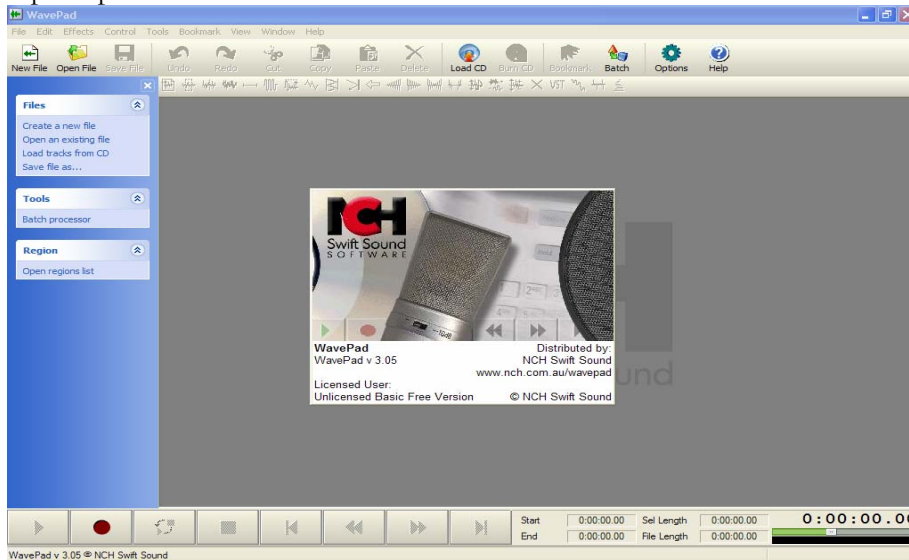
1. In Microsoft Windows go under Start -> Accessories -> Entertainment to open the *Sound Recorder* program.
2. Click the record button to start recording. In order to record you must have a microphone connected to the computer. Click stop to end recording. You can click play if you would like to hear what you have recorded.



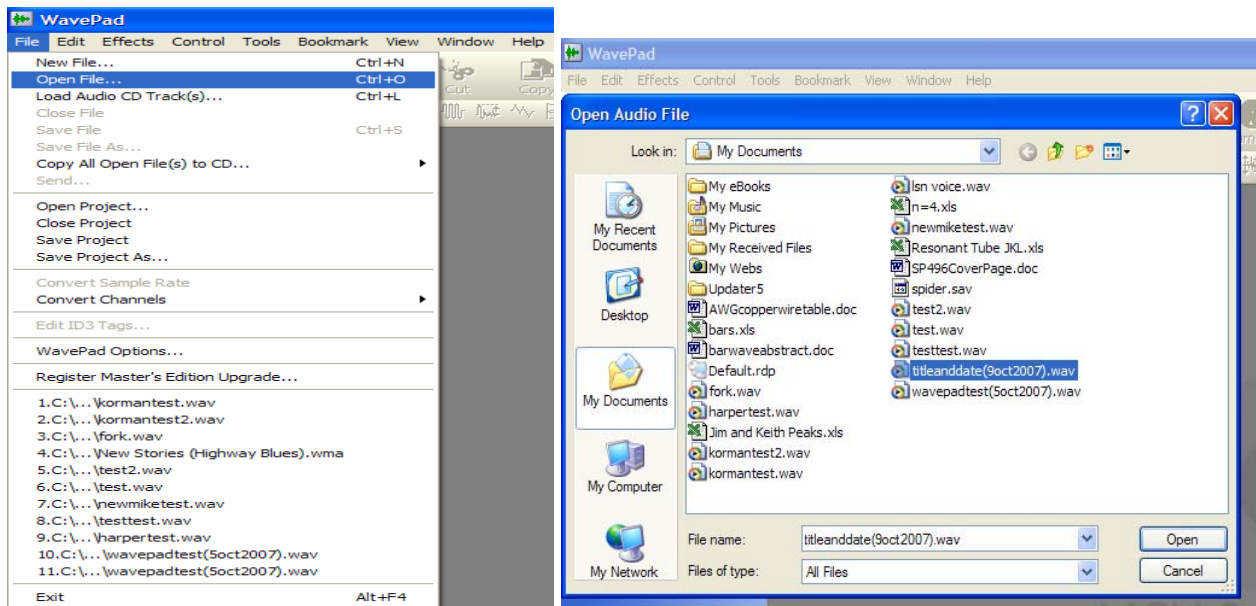
3. Click on File and select Save As. Save the file in wav format. Type in a name and the date for the file and click Save.



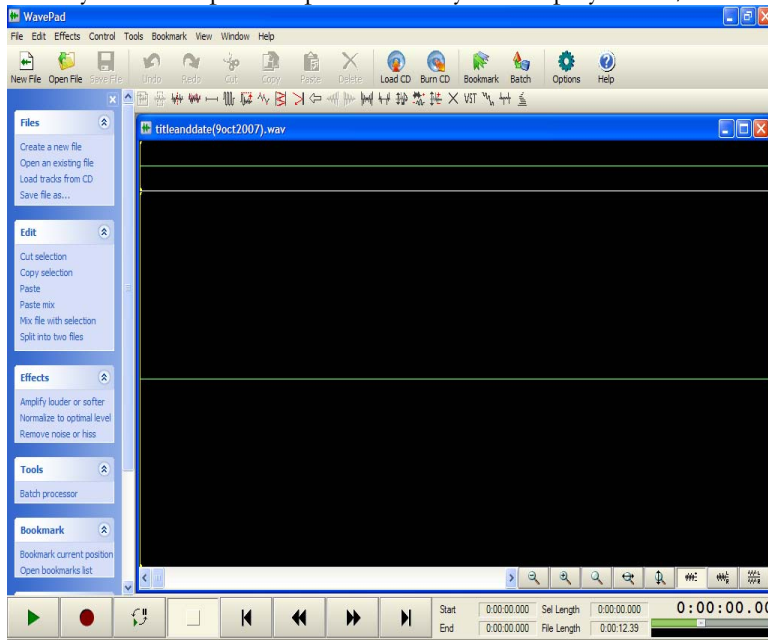
4. Open up WavePad©



5. Click File and select Open File. Find the sound that you have recorded and open it up in WavePad©.

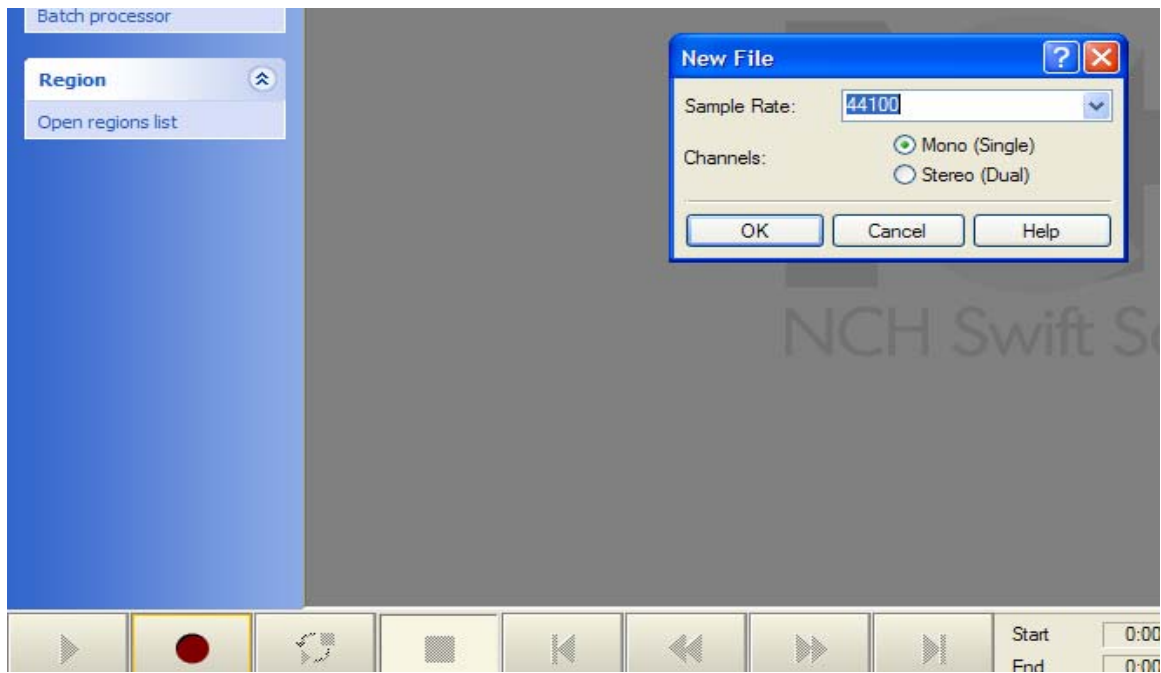


6. Once you have opened up the sound you can play it and/or analyze it.

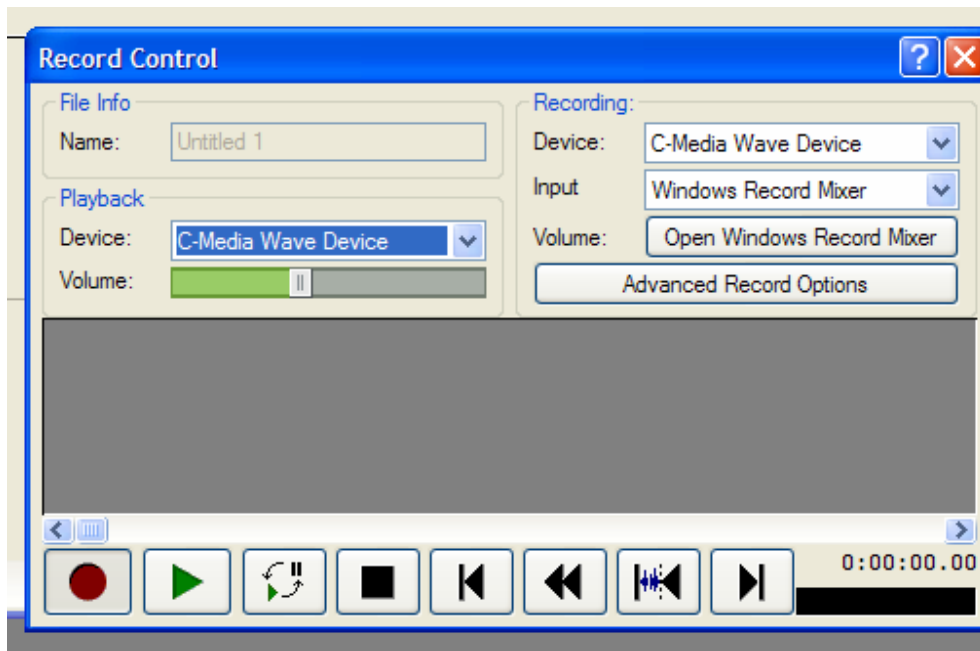


B. Recording and Analyzing Sounds Directly in WavePad©

1. Open WavePad© and click the record button. Choose a sample rate and number of channels. The default setting is shown here. Click ok.

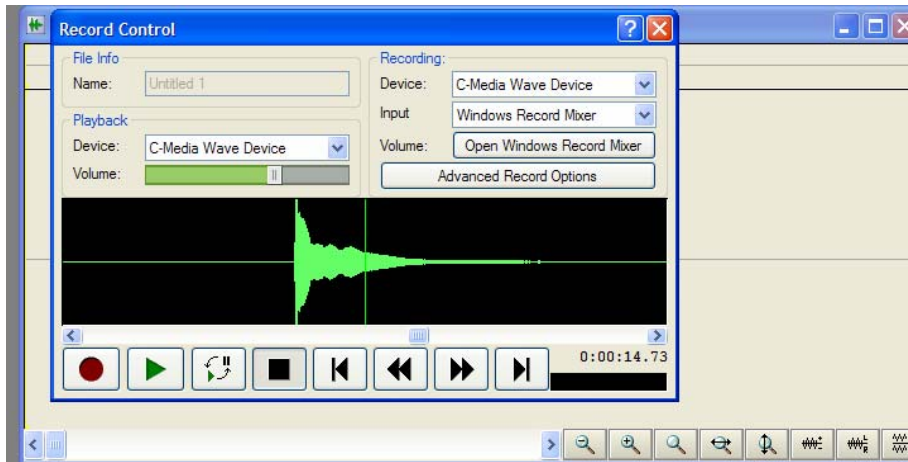


2. A Record Control window will pop up. Choose the playback and recording settings you want. Click the record button to record sounds. Click stop to finish recording.

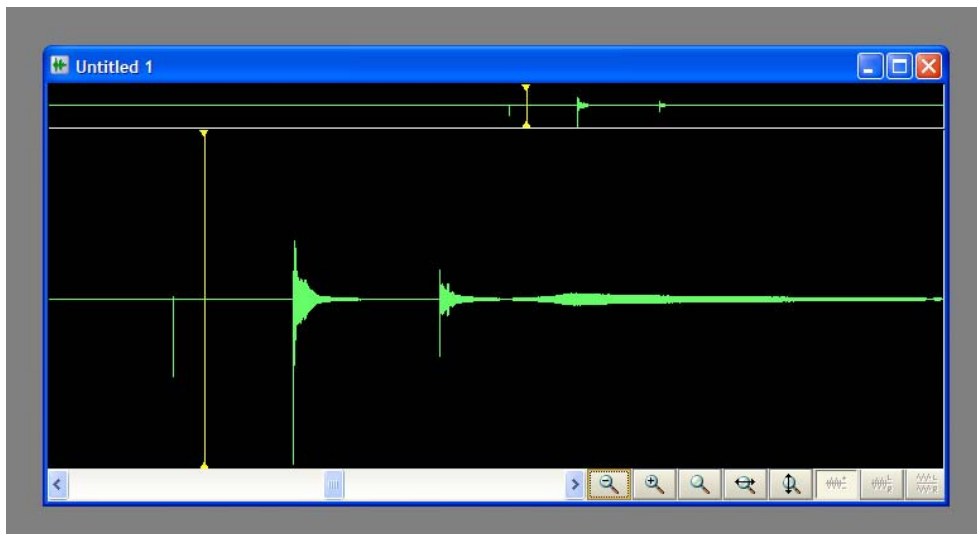


Note: The playback device and recording device must be the same.

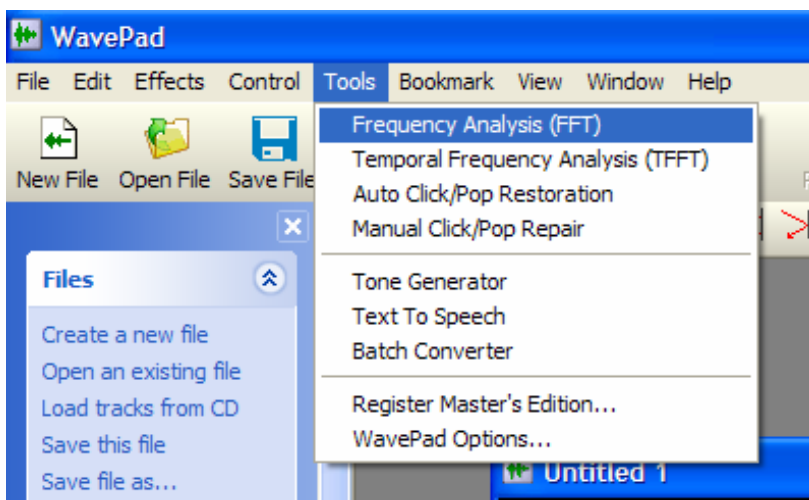
3. Press play to see what you recorded.



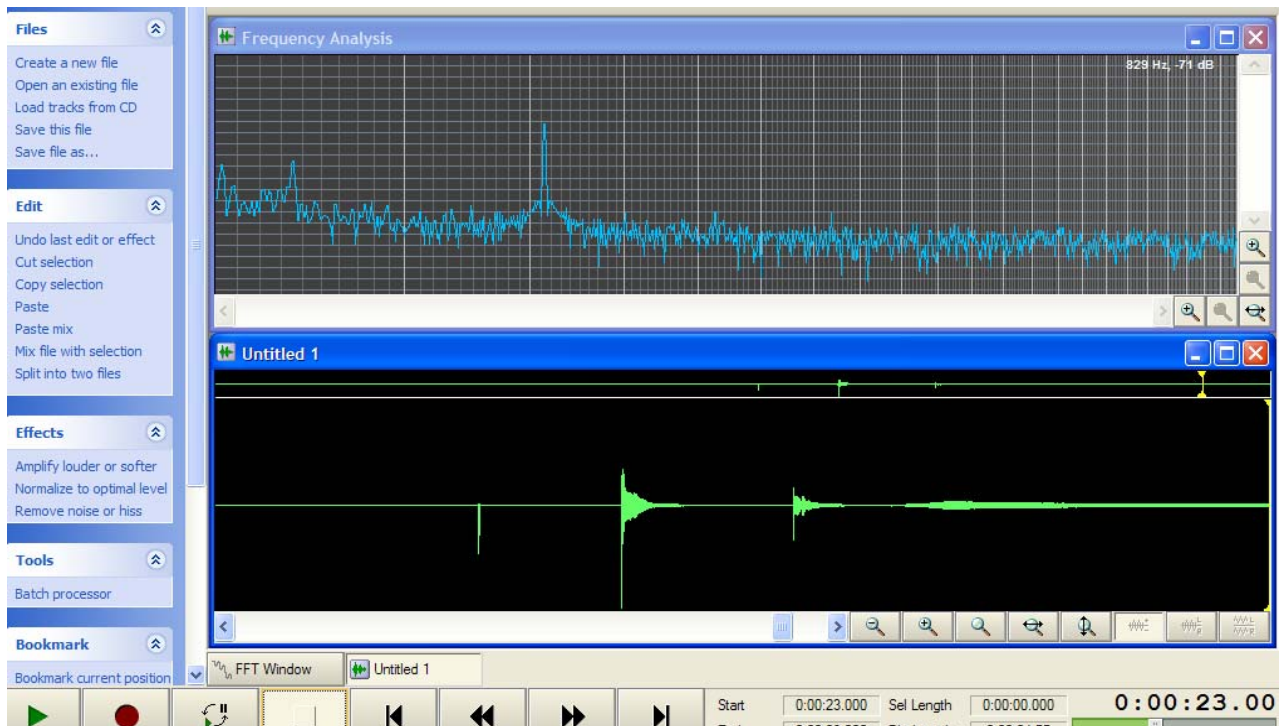
4. Close the Record Control window to view the sound in a file.



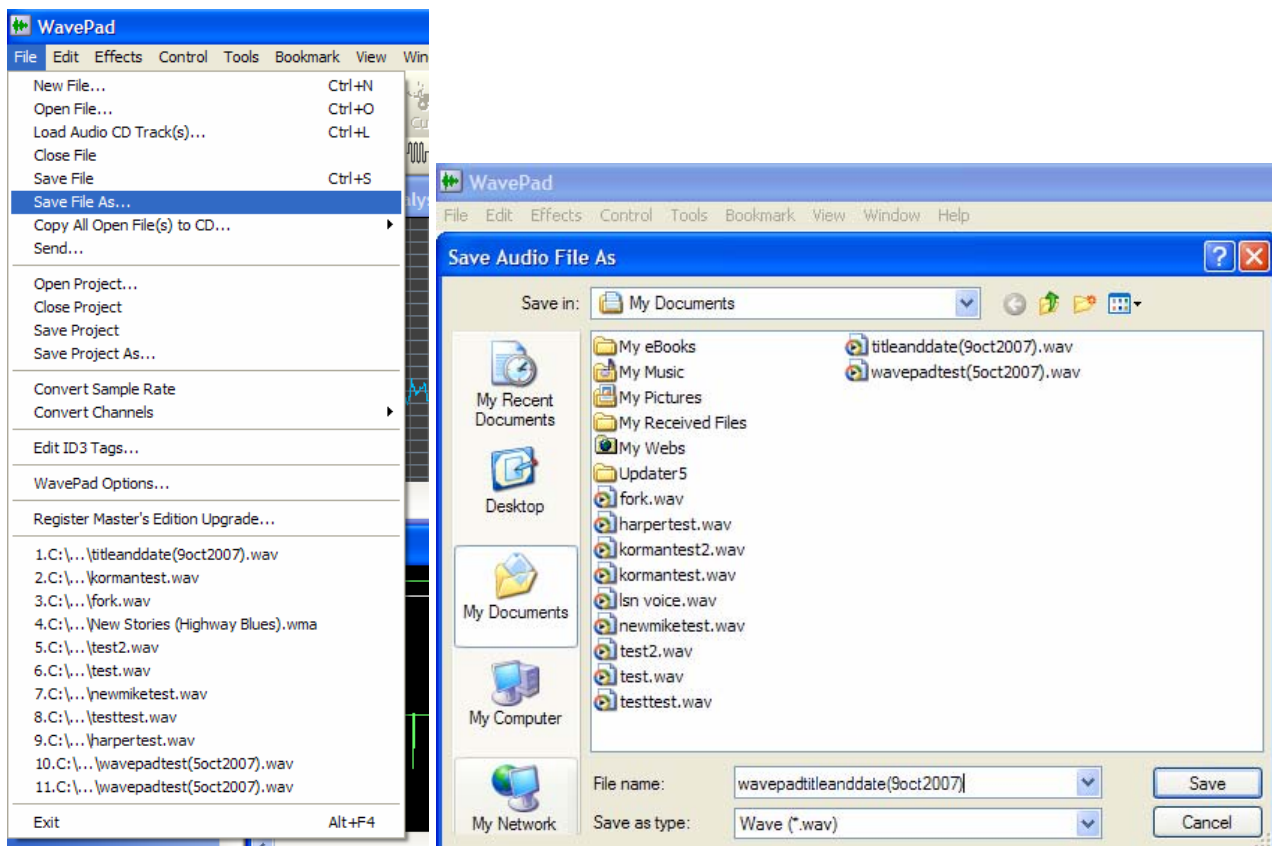
5. Go to Tools and select Frequency Analysis (FFT).



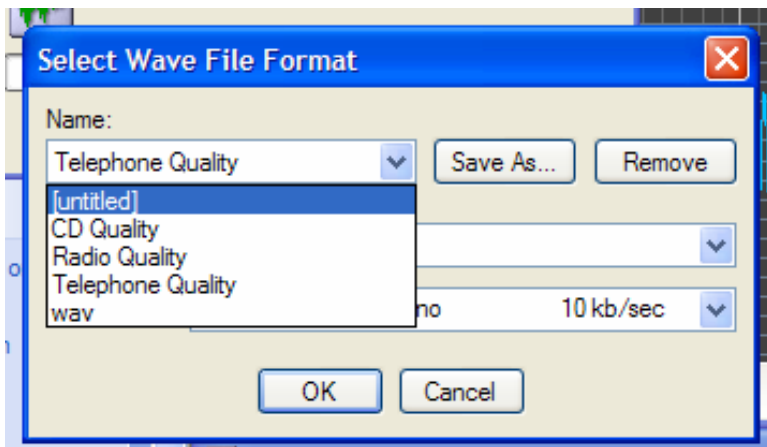
6. Click the play button to hear, see and analyze the sound.



7. Go to File and click Save File As. Name and date the file and save in wav format.



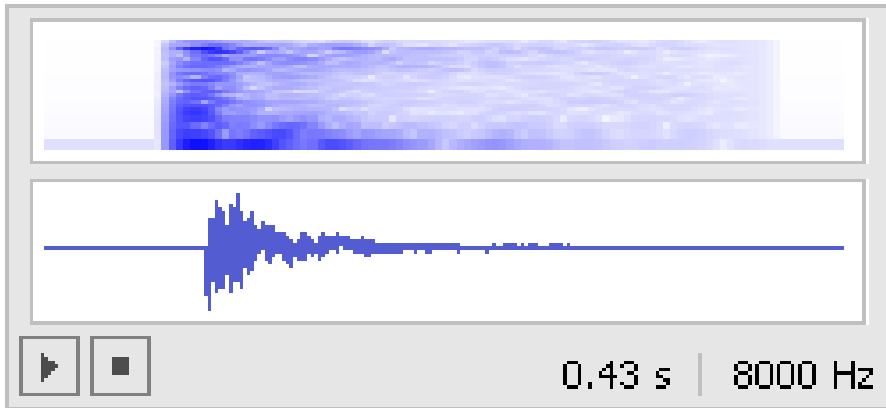
8. Once you click save a Select Wave File Format window will pop up. Change the settings if you desire and click ok.



Appendix 2. Using Mathematica® to load and manipulate wav files

Professor Murray Korman and Rebecca Carr (Acoustics Technician)
United States Naval Academy
Physics Department
11 October 2007

```
Import["CDRexample(23oct2007).wav"]
```



Import wav file into
Mathematica

Load Audio package

```
<<Miscellaneous`Audio`
```

General::newpkg: Miscellaneous`Audio` is now available as the Audio
Package. See the Compatibility Guide for updating information. □

```
CDRex=ReadSoundFile["CDRexample(23oct2007).wav",PrintHeader True];
```

```
Format: Microsoft PCM WAVE RIFF
```

```
Duration: 0.42525 seconds
```

```
Channels: 1
```

```
Sampling rate: 8000
```

```
Bits per sample: 8
```

```
Data size: 3402 bytes
```

```
Number of samples: 3402
```

Execute ReadSoundFile
command

Check out length of data file

```
Length[CDRex]
```

```
3402
```

```
CDRsquared=CDRex^2;
```

```
Length[CDRsquared]
```

```
3402
```

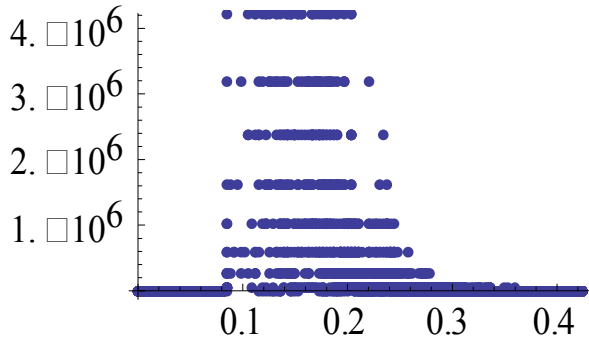
```
time=Range[0,Length[CDRsquared]-1,1]/8000;
```

```
Length[time]
```

```
3402
```

```
datapairs=Transpose[{time,CDRsquared}];
```

```
ListPlot[datapairs]
```



Square the wave

Convert sample point to time

Plot the square of the wave

Average the square of the wave

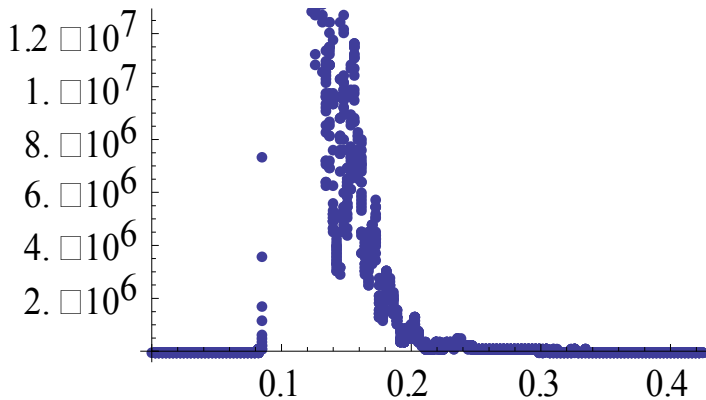
```
avegmod[n_] :=  $\left(\frac{1}{(2*n)+1}\right) * \sum_{i=-n}^n \text{RotateLeft}[CDRsquared,i]$ 
```

```
timeCDR[n_] := Transpose[{time,avegmod[n]}]
```

```
timetrunc1[n_] := Drop[timeCDR[n],n]
```

```
timetrunc2[n_] := Drop[timetrunc1[n],-n]
```

```
p2=ListPlot[timetrunc2[10]]
```



```
dBsmooth=N[10*Log[avegmod[10]+0.01]];
```

```
Length[dBsmooth]
```

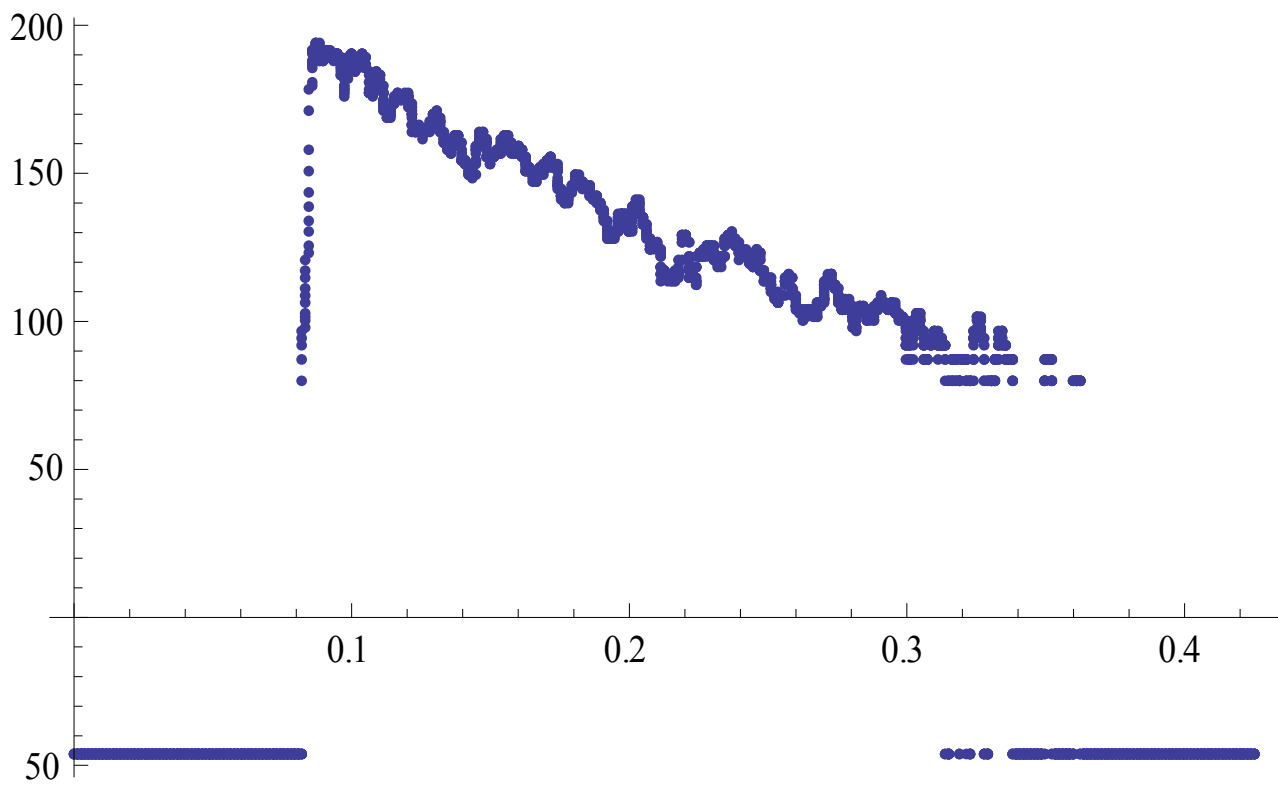
```
3402
```

```
dBsmoothpair=N[Transpose[{time,dBsmooth}]];
```

```
p1=ListPlot[dBsmoothpair]
```

Take the log₁₀ of a squared wave

Create and plot (x,y) list of (time,dB)



```
numberpoints=Length[dBsmoothpair]
```

```
pp=Round[0.20*numberpoints]
```

```
qq=Round[0.30*numberpoints]
```

```
3402
```

```
680
```

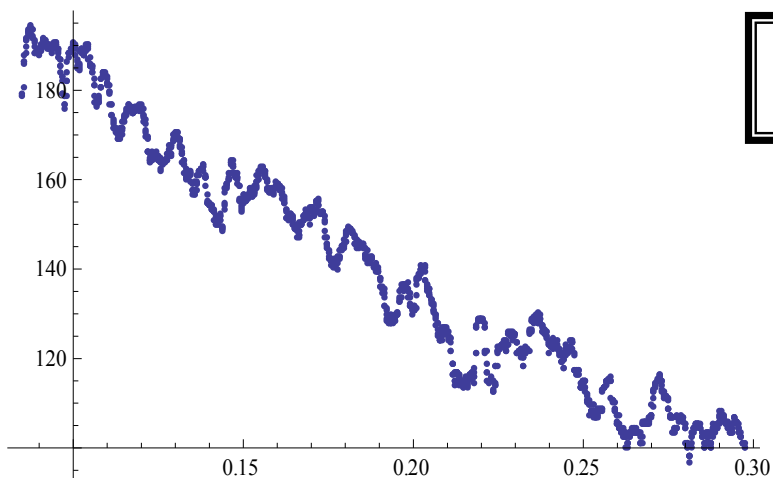
```
1021
```

Truncate the data set to eliminate the endpoints

```
dBsmoothpair1=Drop[dBsmoothpair,pp];
```

```
dBsmoothpair2=Drop[dBsmoothpair1,-qq];
```

```
p3=ListPlot[dBsmoothpair2]
```

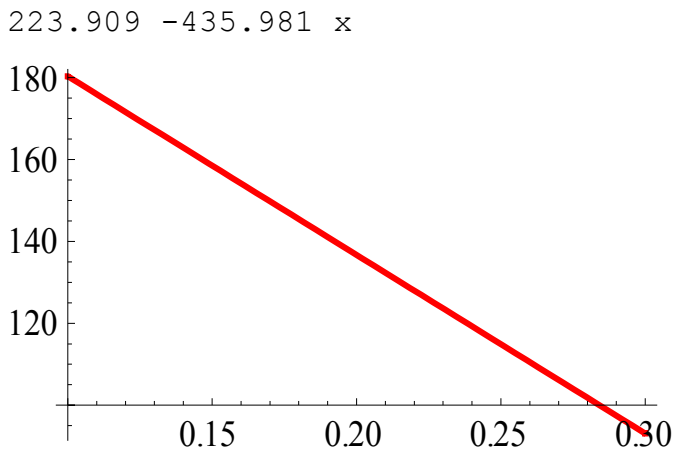


Re-plot data

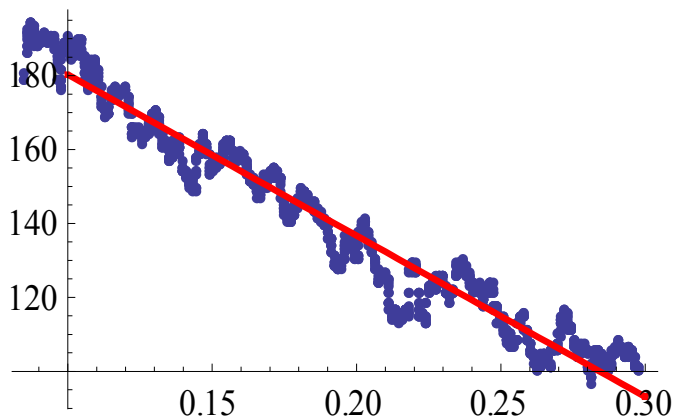
```
fitsmooth=Fit[dBsmoothpair2,{1,x},x]
```

```
p4=Plot[fitsmooth,{x,0.10,0.3},PlotStyle {RGBColor[1,0,0],Thickness[0.01]}]
```

```
Show[p3,p4]
```



Fit a line to the (t,dB) data



From the dB_{max} find the reverberation time by identifying the time when $\text{dB} = \text{dB}_{\text{max}} - 60 \text{ dB}$

```
reverbtime=x/.NSolve[fitsmooth 223.909-60,x]
```

```
{0.13762}
```

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