RSG INC.
RESOURCE SYSTEMS GROUP, INC.

■ NOISE PRIMER

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1. INTRODUCTION

Noise is defined as "a sound of any kind, especially when loud, confused, indistinct, or disagreeable."[1] It often has also been referred to simply as unwanted or "undesired"[2] sound. In order to understand noise, one must understand sound first.

This noise primer will assist you in gaining a basic understanding of sound principles, properties, relationships, and parameters. This primer begins with an overview of basic sound principles, including the properties of sound and how sound is propagated in the environment. The rest of the primer discusses noise standards, and how noise is measured, modeled, and mitigated.

2. BASIC SOUND PRINCIPLES

This section of the primer describes how sound energy is propagated via waves, what a sound level is and how sound moves and changes through space.

2.1. SOUND AS A WAVE

Sound is the rapid oscillation of particles in any medium. Using this definition, the sound we experience day-to-day is the rapid vibration of air that we can sense with our ears. However, sound can also propagate through solids such as steel, rock, or wood and through liquids such as water.

Through air, sound propagates as a compression wave. That is, sound travels as fluctuations of air pressure above and below the atmospheric pressure. Sound can also be described in terms of vibrating of air particles where, at certain points along the wave, air particles are compressed and, at other points, the air particles are spread out.

Figure 1 illustrates two ways of describing sound. The blue section at the bottom shows an example of a compression wave, with air particles represented in blue. The green at the top of the figure shows a transverse wave. A transverse wave is similar to a vibrating string. While sound does not physically propagate as a transverse wave, the transverse wave can be used to describe the two main properties of waves in general: amplitude and wavelength.

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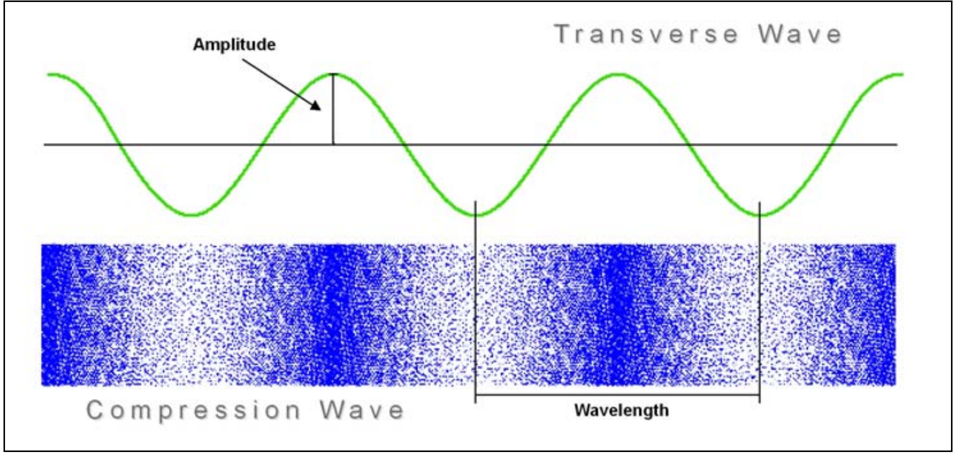
[1] *The American Heritage Dictionary of the English Language*, Houghton Mifflin Company, 1981.

[2] ANSI S1.1-1994, *Acoustic Terminology*

Figure 1: Compression and Transverse Waves



In reference to sound, amplitude is what we perceive as the sound pressure level or how loud a source is. The higher the amplitude of the sound wave, the louder it is. Physically, sound amplitude is a measure of the extent to which the air pressure due to a sound wave fluctuates above and below the atmospheric pressure. In terms of the compression wave shown in Figure 1, amplitude is expressed by how compressed or spread out the air particles are at the various points along the sound wave.

Wavelength is the distance between two maximum compression locations in a sound wave. One wavelength is one complete cycle of the sound wave. Wavelength is important because it is directly related to the frequency of the sound, which is what the human ear perceives as tones. Sound with longer wavelengths are lower frequencies, and shorter wavelengths are higher frequencies. Frequency is dealt with in greater depth in Section 2.3.

The last key characteristic of a sound wave is speed. The speed of sound varies from one medium to another, but for air it propagates around 1127 ft/s (344 m/s) at 68°F. The speed of sound can be used to estimate how far away a lightning bolt is by timing the difference between seeing the bolt and hearing the corresponding thunder.

2.2. SOUND PRESSURE LEVEL

The level of a sound is typically quantified by the pressure it exerts. The air pressures from sound that humans are regularly exposed to range from 20 μPa to over 10,000,000 μPa. In order to scale the range down and better approximate the human perception of relative loudness, we use a logarithmic scale for sound pressure level. The unit used for the logarithmic scale is decibel (dB).

The lower threshold of human hearing is 0 dB at 1000 Hz and the threshold of pain is around 130 dB. A typical conversation in a room is between 50 and 60 dBA ("dBA" indicates that these levels are A-weighted. A-weighting is discussed in section 2.2.2). Figure 2 shows the sound levels of typical activities that generate noise.

Figure 2: Sound Pressure Levels of Common Sound Sources (dBA)

Occupational Noise Measured at the ear	Perception	Everyday Noise	Transportation Noise	Decibels (dBA)	
			Near a jet engine	140	
	Threshold of Pain				
				130	
					Deafening
		Hard Rock Band		120	
Chainsaw				110	
Table saw					
Circular saw					
Bandsaw					
Impact Wrench			Auto horn at 10 feet	100	
Electric hand drill					Very Loud
Snowmobile					
		Riding lawn mower, at ear		90	
Street Sweeper					
		Shop-vac, at ear, outdoors			
			Truck passby, 60 mph at 50 feet		
			Inside car, windows open, 65 mph	80	
			Truck passby, 30 mph, at 50 feet		
		Vacuum cleaner, at ear			
					Loud
			Inside car, windows closed, 65 mph		
				70	
			Car passby, 30 mph, at 50 feet		
	Urban Area				
	Conversational Speech	TV in quiet room		60	
		Microwave oven at 2.5 feet			
			Car passby, 30 mph, at 100 feet		
					Moderate
			Idling car at 50 feet	50	
Office, with computer and HVAC					
	Suburban area				
		Refrigerator at 3 feet			
				40	
					Faint
	Quiet rural area, no wind or traffic			30	
	Quiet night, rural area, no background traffic or wind			20	
					Very Faint
				10	
	Threshold of audibility at 1000 Hz			0	

2.2.1. Decibel Math

Since sound pressure levels are on a logarithmic scale, they cannot be arithmetically added or subtracted to determine the total sound pressure of all noise sources in an area. Sound pressure levels in decibels must first be converted back to standard pressure values, then added or subtracted, and then converted back to the logarithmic scale. An easier method is shown in Table 1. In this method, we need only to know the differences in the two sound levels. For example, say we want to add sources with sound levels of 70 and 75 dBA. The difference in the sound levels are 5 dB, therefore, according to Table 1 we add 1 dB to the higher of the two levels. Thus, the sum of 70 dB and 75 dB is 76 dB.

Table 1: Decibel Addition

If Two Sources Differ By	Add to the higher level
0-1 dB	3 dB
2-4 dB	2 dB
5-9 dB	1 dB
>9 dB	0 dB

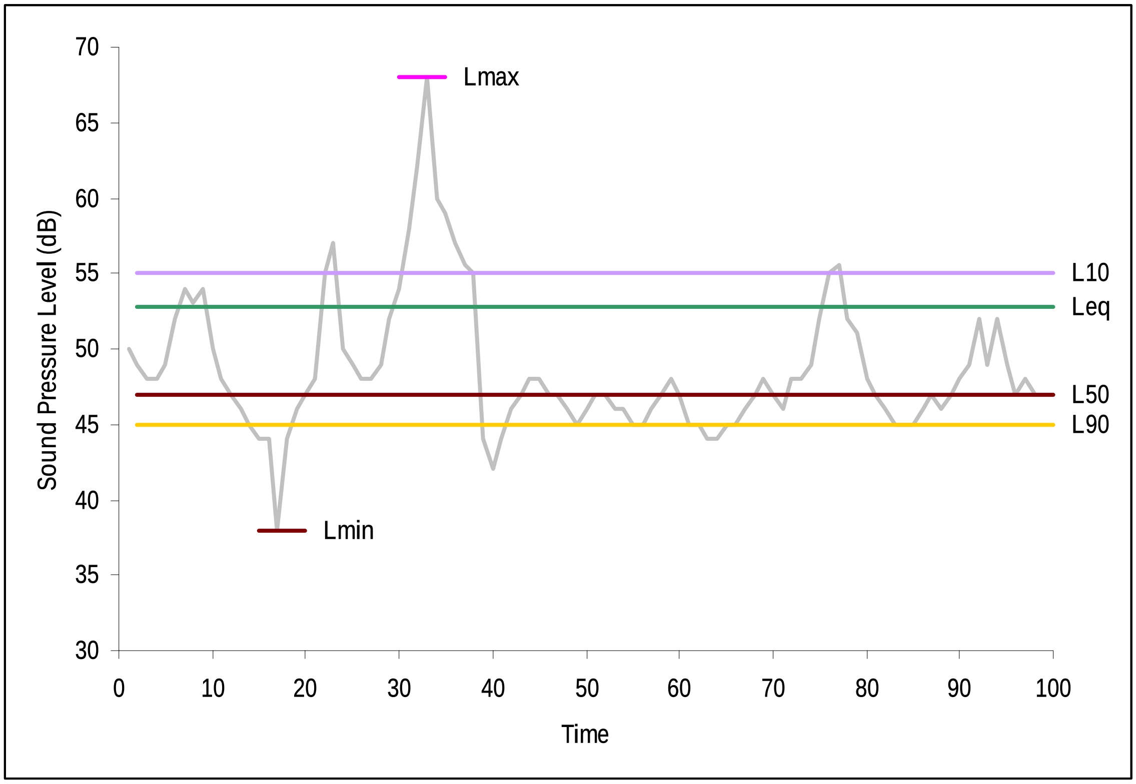
An important consideration in adding sound levels is that for every doubling of the number of sources with the same sound level, the overall sound level increases by 3 dB. For example, if a highway is measured at 65 dBA with 1,000 cars per hour, it will be measured at 68 dBA with 2,000 cars per hour.

2.2.2. Descriptive Levels

Sound can be measured in many different ways. Perhaps the simplest way is to take an instantaneous measurement, which gives the sound pressure level at an exact moment in time. The level reading could be 62 dB, but a split second later it could 57 dB. Sound pressure levels are constantly changing. It is for this reason that it makes sense to describe noise and sound in terms of time.

The most common ways of describing noise over time is in terms of various statistics. Take, as an example, the sound levels measured over time shown in Figure 3. Instantaneous measurements are shown as a ragged grey line. The sound levels that occur over this time can be described verbally, but it is much easier to describe the recorded levels statistically. This is done using a variety of “levels” which are described below.

Figure 3: Example of Noise Measurement over Time and Descriptive Statistics



2.2.2.1. Equivalent average sound level - Leq

One of the most common ways of describing noise levels is in terms of the continuous equivalent sound level (Leq). The Leq is the average of the sound pressure over an entire monitoring period. The monitoring period could be for any amount of time. It could be one second ($Leq_{1\text{-sec}}$), one hour ($Leq_{(1)}$), or 24 hours ($Leq_{(24)}$). Because Leq is the average pressure (expressed in decibels), loud and infrequent noises have a greater effect on the resulting level than quieter and more frequent noises. For example, in Figure 3, the median sound level is about 47 dBA, but the equivalent average sound level (Leq) is 53 dBA. Because it tends to weight the higher sound levels and is representative of sound that takes place over time, the Leq is the most commonly used descriptor in noise standards and regulations.

Similar to a 24-hour Leq is the day-night sound level (L_{dn}). For L_{dn}, a 10 dB penalty is applied to the nighttime Leq between 10 P.M. and 7 A.M.

2.2.2.2. Percentile sound level - Ln

Statistical sound levels, such as the L10, L50, and L90 above give us information about the distribution of sound levels over time. For example, the L10 is the sound level that is exceeded 10 percent of the time, while the L90 is the sound level exceeded 90% of the time. The L50 is exceeded half the time. In the above example, the L90 is a relative base level which most of the sound exceeds, while the L10 is representative of the peaks and higher, but less frequent levels.

2.2.2.3. Minimum and Maximum level – Lmin and Lmax

The absolute minimum and absolute maximum sound levels are often used as environmental noise descriptors. These are represented by Lmin and Lmax, respectively.

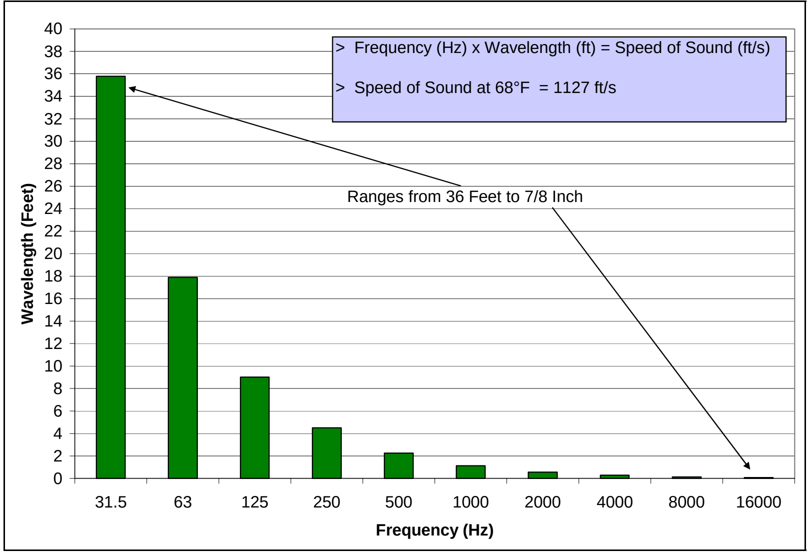
2.3. FREQUENCY

As previously stated, frequency is inversely related to wavelength. The units used for frequency is hertz (Hz),. The relationship between wavelength and frequency is dependent on the speed of sound.

$$\lambda = \frac{c}{f}$$

where λ is wavelength, c is the speed of sound, and f is frequency. Figure 4 shows corresponding wavelengths and frequencies for sound in air at 68°F. As shown, wavelengths in the range of human hearing vary considerably from 56 feet at 20 Hz to less than an inch at 20 kHz.

Figure 4: Relationship between Frequency, Wavelength, and the Speed of Sound



Sound below 20 Hz is known as infrasound. Sometimes, we can perceive frequencies below 20 Hz, but that is typically due to our sense of vibration rather than of hearing. Sound above 20 kHz is called ultrasound and is not perceptible by the human hear.

Most sources are complex and composed of a wide range of frequencies at different sound levels. For sources made up of many frequencies, the range of frequencies and their corresponding sound levels is called frequency spectrum.

Some sources are tonal, like the individual notes on a piano. Others are broadband, like fans. Human speech typically occurs between 200 Hz and 5 kHz

2.3.1 Octave-bands

For analysis purposes, sound is typically broken down into different frequency divisions, or bands. The most common division is the standard octave band. An octave is a band of frequencies whose lower frequency limit is half of the upper frequency limit. An octave-band is identified by its center frequency. As an example, the 500 Hz octave-band contains all frequencies between 360 Hz and 720 Hz. An octave higher would twice this. That is, it would be centered at 1,000 Hz with a range between 720 and 1,440 Hz. The range of human hearing is divided into 10 standardized octave-bands: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz. For analyses that require even further frequency detail, each octave-band is often broken down into three parts or 1/3 octave-bands.

2.3.2. Human Response to Loudness by Frequency

As previously mentioned, sound pressure levels are expressed in terms of decibels. Since the human ear is not sensitive to all frequencies equally, some frequencies (despite being the same decibel level as each other) seem louder than others. For example, a 500 Hz tone at 80 dB sounds louder than a 63 Hz tone at 80 dB. For this reason, acousticians apply frequency “weightings” to sound levels. The most common weighting scale used in environmental noise analysis is the A-weight, which more accurately represents the sensitivity of the human ear. An A-weighted sound level is usually denoted with the unit dBA or dB(A). The C-weighting is often used for high-energy sounds such as explosions.

3. SOUND PROPAGATION

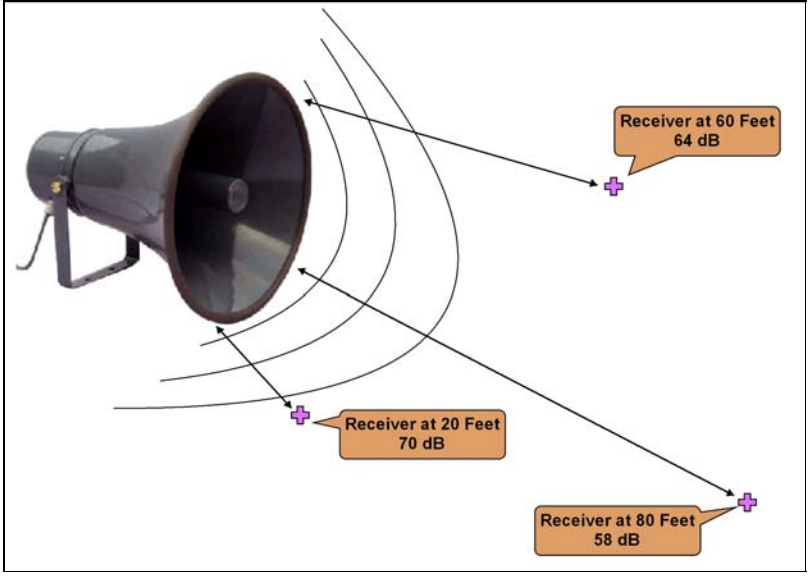
This section of the primer address how sound propagates through the atmosphere. It includes a discussion of factors that affect the level of sound over a distance between the source and receiver.

3.1. SOUND ATTENUATION

As sound propagates from a source, the sound level decreases or attenuates.. Attenuation due to distance is due in part to simple geometry. As the sound moves away from the source, the area that the sound energy covers becomes larger. This means that the sound energy per unit area must decrease as the sound moves away from the source.

For every doubling of distance from a stationary point and over soft ground, the sound level decreases by 6 dB. An example of geometric spreading from a point source is shown in Figure 1. For a line source (e.g., a highway) the sound level attenuates by 3 dB for every doubling of distance.

Figure 5: Geometric Spreading - 6 dB for each Doubling of Distance



At some point while sound is propagating, the sound will likely come into contact with a completely different medium or a similar medium with slightly different properties. When this happens there are six different phenomena that can take place: reflection, diffusion, absorption, transmission, diffraction, and refraction. Each of these phenomena is described in the following sections.

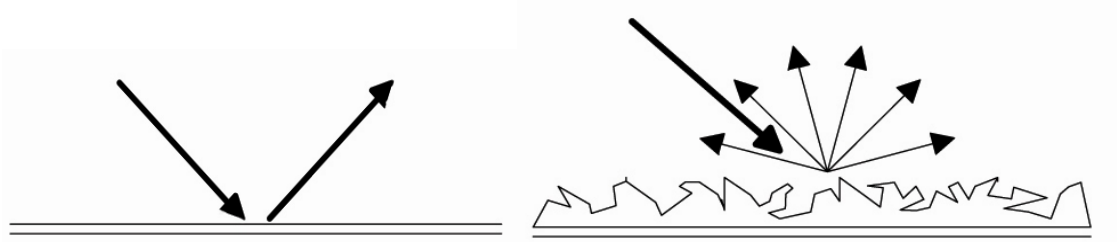
3.2. REFLECTION AND DIFFUSION

Reflection is the simplest action to understand. When sound encounters a surface of a different material, depending on the properties of that material, it has the potential to bounce back off of the surface. Specular reflection occurs when sound propagating from a single incoming direction bounces off a surface and propagates in a single outgoing direction. In order for a specular reflection to occur the reflecting surface must be larger than the wavelength of the incoming sound wave.

A special form of reflection is known as diffusion. Diffusion occurs when sound encounters either an uneven surface or a convex curve. The sound bounces off the surface, but instead of producing a single specular reflection, the sound spreads into many directions. An illustration of specular reflection and diffusion is given in Figure 6.

Sound is reflected and diffused by any solid surface. In environmental noise, the most common sources of reflection and diffusion are the ground and buildings.

Figure 6: Specular Reflection and Diffusion



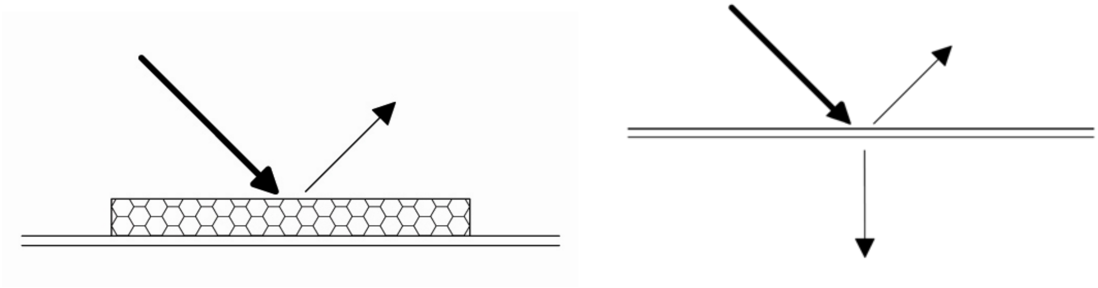
3.3. ABSORPTION AND TRANSMISSION

While sound is reflected when it comes in contact with some materials, when sound comes in contact with another medium some sound energy can be lost. This can happen either through absorption or through transmission. There are many ways sound can be absorbed, but one of the most common ways is through friction. When the air particles that the sound is traveling through comes in contact with a porous surface (e.g., grass, fresh snow, carpet, etc.) friction occurs between the particles and the fibers or edges that make up the porous material. This friction causes a loss in energy and a resulting reduction in sound energy.

Sound can also be transmitted through a medium when it comes in contact with it. This happens when some of the sound energy begins to propagate through the new medium. A common example of transmission is being able to hear something that is on the opposite side of a wall. Figure 7 illustrates absorption and transmission.

In environmental noise, there are several sources of absorption. Solid surfaces such as forest cover and grass will absorb sound. In addition, air absorbs sound, especially at higher frequencies.

Figure 7: Absorption and Transmission



3.4. DIFFRACTION AND REFRACTION

Diffraction and refraction are two acoustic phenomena that cause sound to bend or change direction. Diffraction occurs when sound propagates around a surface or barrier. This occurs when the surface is smaller or similar in length or width to the wavelength of the sound. This happens most commonly near noise barriers or the corners of buildings where you can hear either what is on the other side of the barrier or around the corner, but the source is not within sight.

Refraction occurs when sound enters a medium or when the physical properties of the existing medium change, causing the speed of sound to change. We see this often when looking into a pond or fish tank. We can see a fish in a certain location, but if we put something in the water we can see that that location of the fish is not where we expected it to be. This is because light refracts. When light changes medium from water to air it changes speed and this causes the light to bend. Refraction also occurs commonly in environmental acoustics with changes in the properties of the atmosphere like wind, temperature, and humidity. Since wind, temperature, and humidity all affect the speed of sound to a certain degree, when these properties change from one location to another, sound can bend (refract).

Both diffraction and refraction are frequency dependent. Lower frequencies bend more readily than higher frequencies. This is why sound walls are much more effective at controlling high frequency noise.

4. GLOSSARY OF TERMS

The following is a glossary of acoustical terms. Most definitions are quoted directly or modified from ANSI S1.1, *Acoustic Terminology*.

Acoustics – (a) Science of sound, including its production, transmission, and effects. (b) Those qualities of a room that together determine its character with respect to auditory effects.

dBA – A weighted decibel level

Decibel – Ten times the logarithm of the power function. Expressed as dB.

Equivalent Sound Level (Leq) – The average root mean squared sound pressure over time, expressed in decibels.

Frequency – For a function periodic in time, the reciprocal of the period. Unit, hertz (Hz).

Harmonic – A frequency that is an integral multiple of the frequency of the quantity to which it is related. For example, the first harmonic of 120 Hz is 240 Hz. The second harmonic is 360 Hz. The third harmonic is 480 Hz, etc.

Infrasonic frequency – A frequency lower than the approximate threshold of human hearing of about 20 Hz.

Noise – Undesired sound

Period – Smallest increment of an independent variable for which a function repeats itself.

Pink noise – noise for which the spectral energy is constant across octaves

Reverberation – Sound that persists in an enclosed space after the source of sound is stopped.

Sound – (a) Oscillation in pressure, stress, particle displacement, particle velocity, etc. in a medium (b) Auditory sensation evoked by the oscillation described above.

Sound intensity – Average rate of sound energy transmitted in a specified direction at a point through a unit area. Unit, watt per square meter.

Sound power – Sound energy radiated by a source. Unit, watt (W). The sound power level is often designated as Lw and is expressed in terms of decibels.

Sound pressure – The root mean squared instantaneous sound pressure at a point during a given time interval. Unit, Pascal (Pa). The sound pressure level is often designated as Lp and is expressed in terms of decibels.

Spectrum – The resolution of a signal in different frequencies.

Statistical Sound Level (Ln) – The sound level exceeded N percent of the time. For example, The L90 is the level exceeded 90% of the time.

Ultrasonic frequency – A frequency higher than the approximate threshold of human hearing of about 20 kHz.

Vibration – Oscillation of a parameter that defines the motion of a mechanical system.

Wave – Disturbance propagating in a given direction

Wavelength – The distance between two wave fronts.

White noise – Noise for which the spectrum density is independent of frequency over a specified range.