Sound –101

Many investigators work at capturing EVPs. Most of these investigators have little knowledge of what sound really is. (Not that an EVP IS sound, but more on that at another time). So to bring a little understanding concerning the fundamentals of sound, let me blow my horn.

If a tree falls in the forest, does it make a sound? Because it is a macroscopic event free of quantum mechanical effects, the answer is yes. But what precisely is sound?

A glib answer is that sound is what we hear. But then what is hearing? Hearing is the perception of sound. These circular definitions are a bit worrisome, but have no fear; I'll spend some time describing the physical characteristics of sound—acoustics—and how humans perceive that sound—psychoacoustics.

Sound is simply vibrations in matter. As such, sound requires a medium through which to propagate. By comparison, light requires no transport medium and can travel through vacuum. No matter what you may hear in most science fiction films, sound does not travel through a vacuum, no matter how big the explosion is.

Audible sounds are those vibrations that we hu-mans can hear. Most of the sounds humans hear are transmitted through the air, although audible sounds can also be transmitted through liquid and solid matter. Airborne sound travels in the form of longitudinal waves.

Longitudinal Waves
Consider a long spring or Slinky' stretched out along a table. One end of the spring is fixed in place. The other end is attached to a crank-driven piston. If the crank is quickly turned, the piston compresses the coils of the spring nearest it. This region of compression propagates to the other end of the spring. As the crank continues to turn, the piston moves away from the spring, creating a region of decreased coil density in the coils nearest it. Again, this region of expansion or rarefaction propagates along the spring.

If we keep turning the crank, the piston continues oscillating, and in turn creates localized fluctuations in the coil density. These fluctuations are known as waves, and in this particular case are longitudinal waves because the waves oscillate in the same direction that they are traveling.

The Slinky example is very useful, as it is analogous to how sound behaves in air. Note that the slinky does not move. One end oscillates back and forth a short distance, but the spring as a whole does not make any forward progress.

Waves do move through the medium of the spring. These waves consist of alternating regions of compression and rarefaction. Compression refers to regions of higher density. Rarefaction refers to regions of lower density. Also note that there is an ambient coil density that the spring has before the piston begins moving.

In our thought experiment, the longitudinal waves are transmitted through the compressible medium of the spring. These are, technically, sound waves, although they are not audible to humans. The sounds we are most familiar with are those that move through air. These sounds consist of longitudinal waves passing through the media of air molecules.

Air has an ambient pressure. Sound waves are localized density fluctuations within this medium. Just as with our spring example, air molecules only oscillate when they are carrying sound; they do not move forward in the direction of the sound wave.

Sound waves can travel through most types of matter. We are most familiar with sound moving through air, but it can move through other gases, as well as liquids and solids.
In fact, the density of the universe was so great during its first 300,000 years that sound waves were able to ripple throughout it. The minute density fluctuations of these first sounds are thought to be responsible for the ultimate formation of galaxies and clusters. Alas, most sounds we hear today do not have the same import.

Propagation of Sound

Now I've pointed out some characteristics of sound from the vantage of a fixed point in space. Now we will consider how sound moves through space or propagates.

Diagramming Sound Movement

In diagramming how sound moves, we will be using two conventions: wave fronts and rays.

Wave Fronts

A convenient way to diagram the propagation of sound waves is by arbitrarily picking points of uniform density and plotting these wave fronts as lines. Each successive wave front is parallel to one another. This is known as Planar wavefronts.

Omnidirectional sounds are characterized by spherical wave fronts. For instance, the sound of a firework shell exploding in the air would create spherical wave fronts. The curvature of spherical wave fronts is very apparent close to the source of sound, but from very far away, the wave fronts would appear nearly planar in shape.

Wave fronts are a useful tool as we explore how sound moves through different types of environments.

Sound Rays

Although wave fronts are very useful for diagramming certain acoustic behavior, some concepts are more clearly illustrated using sound rays. These rays are arrows indicating the direction the sound is moving in.

Speed of Sound

So just how fast do sound waves move? The speed of sound varies depending on inertial properties such as density and the elasticity of the medium through which the waves are moving. As such, the speed at which sound moves through air depends upon the local atmospheric pressure, temperature, humidity, altitude, CO_2 concentration, and other related factors.

The speed of sound through air at standard temperature and pressure (STP), 20 degrees Celsius and 101.3 kilopascals, is 1,129 feet per second (344 meters per second).

Speed of Sound in Various Materials

Matter	c (ft/s)	c(m/s)
air (STP)	1,129	344
air (32℉, 0℃)	1,086	331
marble	12,500	3,810
cork	1,640	500
brick	11,975	3,650
water	4,911	1,497
seawater	5,023	1,531
paraffin	4,265	1,300
castor oil	4,845	1,477
oak	12,631	3,850

The speed of sound is designated with the letter c. The letter c is more commonly used to designate the speed of light. However, in this book c refers to the speed of sound unless otherwise noted.

The speed of sound is independent of the frequency or intensity of the sound. In general, all sounds move at the same speed within the same medium. For the sake of completeness, know that extremely loud sounds—sounds that will deafen a human—may have enough power to cause localized temperature fluctuations that may result in some frequencies moving at higher speeds than others.

Wavelength

Now that we know how fast sound is moving, let us consider how far apart the wave fronts are. The distance between adjacent wave fronts is known as the wavelength. The wavelength (λ) of a pure tone is inversely proportional to its frequency, as indicated by the relationship expressed in
the following Equation:

Wavelength and Frequency $c=f - \lambda$

Note that wavelength of a sound at a given frequency also depends on the local speed of sound. The wavelength of a 1,000-hertz tone in air is different than the wavelength of a 1,000-hertz tone in seawater.

Example

Given a pure tone of 5,000 hertz in air at STP, what is the wavelength of the tone?

Solution

$c=f - \lambda$

$\lambda = c/f$

λ = (1,125 feet/second) / (5,000 hertz)

λ = 0.225 feet

Reflection

Sound waves can reflect off objects. Waves hitting an acoustically reflective surface bounce off it in another direction. The direction of reflection is such that the angle at which it hits—the angle of incidence (θi)—equals the angle of reflection (θx). The angles of incidence and reflection are measured with respect to the surface normal. The surface normal is a line perpendicular to the reflective surface.

We can focus sound by taking advantage of the way it reflects. A parabolic reflective surface redi-rects parallel rays of sound to a focal point. Because all the sound is being concentrated into a small region, the resulting pressure—and hence loudness—associated with the sound is greatly increased. This technique is used for amplifying distant sounds, as in the parabolic microphones used in recording on-field dialogue during football games.

Refraction

Rather than reflecting off an object, some sound waves may refract through the object. Sound waves that are transmitted into the new media are bent.

In most cases, the angle of incidence does not equal the angle of transmission. The angle of trans-mission is dependent upon the angle of incidence and the speed of sound in the two materials. The relationship is quantified by Snell's Law. Snell's Law holds that the ratio of the sine of the angle of incidence to the angle of transmission is equal to the
ratio of the speed of sound in the original medium to the speed of sound in the refractive medium.

As sound hits the new medium, the frequency remains constant, but the wavelength changes.

In addition to occurring across well-defined boundaries such as an air-water interface, refraction also occurs in regions with gradual velocity changes. For instance, in the evening, the air next to the earth is warm while the air higher up is cooler. Sound travels slower in the cooler air, causing sounds made near the ground to bend upwards. In such a situation, sound does not carry across the ground as far as it would in the daytime because it is being bent upwards. In the mornings, the reverse scenario can happen; cool air near the ground bends sound waves back towards the Earth. Spherical waves that would otherwise have traveled away from the ground are redirected downwards, causing sounds to be heard more
clearly than they would have otherwise.

Diffraction

In addition to reflection and refraction, energy carried as waves (including sound) also diffract. Diffraction is the tendency of waves to bend around obstructions in their path. As such, you can sometimes hear sounds even if there is an object between you and the source of the sound. The region behind the obstruction, which the sound waves do not reach, is
the shadow zone. The amount of diffraction depends upon the size of the obstruction and the wavelength of sound. If the wavelength is very large compared to the obstruction, then the diffraction is so great that there is almost no shadow zone at all. For instance, you can hear a tone with a 10-foot wavelength from behind a toothpick with no trouble at all.

Conversely, if the wavelength is small compared to the size of the obstruction, then there is a large region behind the obstruction that the sound waves cannot reach through diffraction.

As we will study in more detail in the following chapter, the diffraction of sound waves around the human head is one of the cues used for locating the position of sounds.

Interference

When sound waves occupy the same point in space, they interfere with one another. The resultant intensity of coincident waves is simply the sum of the intensities of the individual waves, a principle known as superposition.

If two identical waves interfere with each other, the resulting wave has the same frequency as the original waves, but is twice as intense. Such a combination is known as constructive
interference. Now suppose one of the waves is in phase opposition to the other. When these two waves are added together, they cancel each other out, resulting in no waves. This nullification is known as destructive interference. It may seem odd that playing two sounds of equal intensity results, in a net silence, but it is a very real phenomenon. In fact, it is used by pilots, and now consumers, in noise-canceling headphones that cancel out ambient sounds. I am currently developing a system similar to this that will remove adjacent platform crosstalk at train stations.

Beat Frequency

When two waves with similar frequencies interfere with one another, they exhibit what is known as a beat frequency. Even though the two original signals have a constant intensity,
the combined signal's intensity sinusoidally varies between zero intensity and the combined intensity of the original two signals. The rate of this intensity oscillation is known as the
beat frequency. The beat frequencies are used by musicians to tune their stringed instruments. If they play a reference tone from a tuning fork or electronic tuner, and then pluck the string being tuned, an out-of-tune string has a beat frequency. The higher the beat frequency, the more out of tune the string is. By adjusting the tension on the string until the beat frequency becomes zero and disappears, they can bring the string into tune.

Doppler Effect

When a fire engine races past us, the frequency of its siren seems to change. Obviously, the frequency produced by the siren remains constant. Firemen riding in the truck hear the same constant frequency. However, to stationary observers, the frequency is higher as the truck approaches and is lower when the truck recedes. What is happening is that the truck's motion is compressing the wave fronts in front of the vehicle and spreading them out behind. Because frequency is inversely proportional to the wavelength, the siren's frequency is higher to stationary observers in front of the moving truck, and lower to stationary observers behind the truck.

This phenomenon is known as the Doppler Effect, after Christian Doppler, who conceived the idea in 1842. The Doppler Effect holds true for other waves, such as light. Indeed, one of the biggest break-throughs in astronomy came in 1929 when Edwin Hubble examined the Doppler shift of the light being produced by nearby galaxies and found that almost all of them are moving away from us at very high speed. The Doppler Effect also applies to moving observers and stationary sound sources. However, the amount of frequency shift for an observer moving past a stationary source at a given speed is different than the frequency shift of a sound moving at that same speed past a stationary observer. In other words, the siren sounds different if the truck is moving towards you at 50 miles per hour (MPH), than if you were moving towards it at 50 MPH.

Sound Intensity and Power

I've discussed how sound moves through a medium, and I've also discussed some characteristics of sound such as frequency, wavelength, and speed. I will now explore another characteristic of sound: intensity.

Humans can hear sound with a wide range of intensities. The range is so vast that it is often unwieldy to deal with the intensity values if they are all arranged evenly. Furthermore—as I will discuss in great detail later, human perception of sound is non-linear. A small change in intensity of a low intensity sound is much more noticeable than the same amount of change in a high intensity sound. For these reasons, we often apply logarithms to acoustic measurements. Logarithms have the advantage of compressing higher numbers close together.

Logarithms

It used to be that the only way to figure out a logarithm was by buying an expensive reference book and looking up the answer in a table. The advent of the slide rule meant that with just a little training, anyone could readily compute a logarithm by sliding bits of wood and plastic from side to side with great precision. The tricky bit was keeping track of the power of ten. Was the answer 0.0125 or was it 0.00125? Today, of course, to compute the logarithm of a number, you just type in the number into a scientific calculator and press the log button.

A logarithm or log is defined to be log b (x) = y, such that by=x. For instance, log 10100=2, because 102=100.

Unless explicitly stated otherwise, the base of a logarithm is assumed to be 10, because that's how many fingers we have. As such, rather than writing log 10(x), we often just write log(x).

You may sometimes see log e (x) (where e is ~2.7182818). This logarithm is known as a natural log, and is typically abbreviated ln(x). Also, logarithms with a base of 2 are common, and log2(x) is often abbreviated as lg(x).

Decibels

There are many examples in the field of sound where we take the logarithm of a ratio of values. Being a ratio, the number is unit-less. However, to provide a descriptor of what the number is, the term Bel is used. The Bel is named after Alexander Graham Bell.

For example, if we wanted to compare a 100-watt (W) power source to a 20-watt power source, we would say the logarithm power ratio is log(100W/20W)= log (5)= 0.699 Bels. For common sound measurements, the Bel is too large a unit, so we instead use a tenth of a Bel, also known as a deciBel (dB). The capital B is often omitted when writing out the term, giving us decibel. However, the abbreviation properly maintains the capital B (dB). I will explore the concept of decibels in greater detail after I first introduce thetypes of measurements that use decibels.

Sound Power

When something makes a noise, it is using energy to create oscillations in the air. Because energy is conserved, what is really happening is that energy of one form is being converted into another form. For instance, a loudspeaker converts electrical energy into the kinetic energy of a vibrating diaphragm. The rate at which energy is converted over an interval of time is known as power. When the energy in question is being used to create sounds, the power is known as acoustic power or sound power.

In the field of acoustics, power is most often measured in units of the watt (W). Many of us are familiar with watts as a measurement of the power consumption of light bulbs. The acoustic power examples are shown below:

Acoustic Power of Some Common Objects

Item	Max Acoustic Power (Watts)
Boeing 777 at full throttle	8,000
75-piece orchestra	75
250 watt cinema loudspeaker	7.0

Many sound devices, such as speakers and amplifi-ers, are often described with a wattage value, as in 30-watt speakers. Almost invariably, the wattage listed is referring to the electrical power the device can handle. The acoustic power the device can produce is always much less than the electrical power. The sound power of a device is sometimes measured against a reference sound power of 10-12 W. The
logarithm of this ratio is taken to give the Sound Power Level, which has the somewhat counterin-tuitive acronym of PWL. The PWL is defined in the following equation:

Sound Power Level

PWL (dB)= 10 log (W/W0), where W0= 10-12 watts

The 10 in the equation is there to convert from Bels to decibels. As we will soon see, PWL is not the only measurement to use decibels. As such, to clarify that a particular decibel measurement is of the Sound Power Level, the number is often annotated as dB-PWL.

Example

What is the sound power level of a 100W loud-speaker that is producing 3.0W of acoustic energy?

Solution

PWL= 10 log(W/W0)

PWL= (3 watts/10-12 watts)

PWL= 10 log (3-1012)

PWL= 125 dB-PWL

Sound Intensity

A measurement of sound power level does not vary with distance from the sound source. By analogy, a 75-watt light bulb always has a power level of 75 watts. It does, however, appear brighter when you are one foot away from it compared to when you are five light years away from it. Similarly, sound intensity is a measurement which is very much dependent on distance from a sound source. The closer you are to a sound power source, the higher the sound intensity is. Sound intensity is formally defined as the acoustic power applied over an area, as shown in the equation below. Humans can hear sound intensities ranging from roughly 10-12 W/m2 to 1 W/m2.

Sound Intensity

sound intensity = acoustic power / area

For a simple case, imagine an omnidirectional sound generator located in a free space where we don't need to worry about reflections. At a distance r from the source, the power would be applied over the surface area of a sphere of diameter r. Given that the surface area of a sphere 4πr2, the intensity of this sound would be given by this equation:

Sound Intensity of an Omnidirectional Transmitter in a Free Field

sound intensity = acoustic power / (4πr2)

We can see from the equation that intensity is inversely proportional to the square of the distance from the source. If we double our distance from the sound source, the intensity of the sound is quartered. This relationship is also known as the inverse squares law. It holds with our everyday experience of sounds: the further away we are from a sound generator, the less its intensity is. In the real world, not all sounds are omnidirectional. A loudspeaker, for instance, directs most of its power toward the front and very little to the rear. Furthermore, most sounds do not occur in a free field, but reflect off the ground, trees, walls, ceilings, or other obstructions. These same objects can cause the sound waves to refract and diffract, further altering the distribution of acoustic power. It is subsequently very difficult to accurately measure sound intensity in the real world. It is, however, relatively easy to measure sound pressure.

Pressure

As we've discussed earlier, sound consists of localized fluctuations in the ambient pressure.

Pressure is a force acting over an area. A common pressure measurement we use in everyday life is measuring the pressure of the tires on our car or bicycles. Most automobile tires are inflated to a pressure on the order of 30 pounds per square inch (psi). Every square inch inside the tire feels as much pressure against it as would be exerted by the gravitational force of a 30 pound weight.

Of course, most of the world is still using the metric system. The metric unit of force is the Newton. Pressure is thus measured in units of Newtons per square meter (N/m2). The Pascal (Pa) is a unit of pressure defined to be 1 N/m2. The pressure change required for a sound to be audible to humans is quite small. In fact, humans can hear sound pressure differences as small as 20 microPascals (µPa). By comparison, atmospheric pressure is 101.3 kiloPascals (kPa). That means we can hear variations in pressure that are five bil-lionths smaller than the ambient air pressure. If we had the same accuracy in visually detecting changes in distance as we do detecting changes in ambient pressure, we would be able to discern variations in the moon's distance from the Earth on the order of three inches!

Although it is much easier to measure sound pres-sure than sound intensity, intensity is a more use-ful measurement. It turns out that sound intensity is proportional to the square of pressure. If we wanted to get a measurement of intensity, we could derive it from the pressure by applying a little math:

10 log(Intensity1/Intensity0) =
10 log ((Pressure1/ Pres-sure0)2) =
20 log (Pressure1/ Pres-sure0)

This last step comes courtesy of the equality log(xy)= y log x. From this exercise, we have derived a useful acoustical measurement known as the Sound Pressure Level (SPL). The SPL provides sound intensity by comparing the measured pressure against a reference pressure associated with the quietest sound a human can hear (known as the threshold of hearing), as shown in the following equation:

Sound Pressure Level

SPL = 20 log (P1/P0), where P0= 20 µ Pa

To clarify that a particular decibel measurement is of the sound pressure level, the number is often annotated as dB-SPL.

Example
A handheld sound level meter indicates that a nearby jackhammer has a sound pressure level of 85dB-SPL.
What is the sound pressure of the jackhammer?

Solution
$SPL = 20 \log (P1/P0)$
$(SPL/20)= \log (P1/P0)$
$10(SPL/20)= P1/P0$
$P1= P0- 10(SPL/20)$
$P1= 20\ \mu Pa - 10(85/20)$
$P1= 20\ \mu Pa - 10(85/20)$
P1= 347 milliPascals

Remember that the SPL is dependent on distance from the sound source, as well as the geometry and location of reflective and refractive objects in the environment. Keeping that in mind, I have provided a list of the SPL of some common sounds in typical situations. Note that prolonged exposure to sounds above 100 dB result in permanent hearing loss.

SPL of Some Common Objects

Sound	SPL (dB)
Whispering	10-20
Quiet Library	30
Ordinary conversation (at 1.5 feet)	65
Vacuum cleaner	75
Heavy traffic	85
Siren (at 100 feet)	100
Rock Concert	120
Threshold of Pain	120
Jet engines (at 100 feet)	140

Decibels Revisited

Now that we've introduced Sound Power Level (PWL) and Sound Pressure Level (SPL), let's spend some more time getting familiar with measuring them in decibels.

Remember that decibels are logarithmic ratios. As such, you cannot simply add them. For example, a 15dB-PWL sound source combined with another 15dB PWL sound source does not result in a PWL of 30dB. Instead, the combined PWL is 18dB, as we shall see in the following example.

Example
Suppose you have two sound sources which each have a PWL of 15dB. What is the combined PWL of the two sources?

Solution
For starters, let's compute the PWL of the first speaker.

PWL= 10 log (W1/W0)
(PWL/10)= log (W1/W0)
10(PWL/10)= W1/W0
W1= W0- 10(PWL/10)
W1= W0- 10(15/10)
W1= 31.6 - 10-12 W

We know that the two sound sources have the same PWL, so W2= W1. The total power is just the sum of the two individual power sources.

WTOTAL = W1 + W2.
WTOTAL = 63.2 - 10-12 W

Right, so now let's compute the PWL of the two sound sources.

PWLTOTAL= 10 log (WTOTAL/W0)
PWLTOTAL= 10 log (63.2 - 10-12 W /10-12 W)
PWLTOTAL= 18.0 dB

Note that doubling the power resulted in a PWL increase of 3dB (from 15.0 to 18.0 dB-PWL). In fact, doubling any power level results in a 3 dB increase in PWL. Conversely, halving a power level results in a 3 dB decrease in PWL.

The same doubling-3dB relationship holds true for SPL as well, with some caveats. When we are dealing with random noise, the relationship holds. However, we have already discussed that sound waves interfere with one another. If you added two coherent sine waves with 15 dB-SPL together, and they were exactly out of phase, they would cancel each other out. The resultant pressure from the two sounds would be zero, resulting in an SPL of - ∞ dB. Such scenarios are not common in most real world situations.

Example
Two sound sources have a combined SPL of 50 dB. Turning off the first sound source reduces the SPL to 45 dB. What would be the SPL if just the first sound source was turned on?

Solution
First, let's figure out the total pressure.

PTOTAL= P0- 10(SPL/20)
PTOTAL= 20 µPa - 10(50/20)
PTOTAL= 6324 µPa

Now let's figure out the pressure from the second sound source.

P2= P0- 10(SPL/20)
P2= 20 µPa - 10(45/20)
P2= 3557 µPa

Next we can determine the pressure from the first sound source.

P1= PTOTAL - P2
P1= 6324 µPa - 3557 µPa
P1= 2767 µPa

Finally, we can compute the SPL in dB above the reference.

SPL1 = 20 log (P1/P0)
SPL1 = 20 log (2767 µPa /20 µPa)
SPL1 = 42.8 dB

I hope this has cleared up the mud a bit.

References here are from Sound System Engineering, Second Edition, By Davis and Davis.