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The Science of Sound: Acoustics and Soundscape Measurement

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Introduction

Soundscapes have emerged in recent years as a key issue in national park management. In 2000, the National Park Service created the Natural Sounds Program specifically to help implement soundscape policy. This paper explains the basics of sound, sound pressure, frequency, and other units of measure. It shows how these acoustics measures might be applied in soundscape management.

What is sound?

Sound is a pressure variation in air or other media that is within the hearing range of a given species. It is a physical phenomenon having two dimensions: amplitude and frequency.

Amplitude is the magnitude of sound pressure. It is measured in Pascals (the metric equivalent of pounds per square inch). The range of pressures that a human can detect is greater than 1,000,000:1. Because of this very large range, a logarithmic scale is used. A decibel is the logarithm of the ratio of the measured pressure to a reference pressure. When decibel values are given, they are usually expressed as dBA, which means that the scale (A-weighted) has been adjusted to human hearing by setting the threshold for human hearing at zero decibels.

Frequency is the number of pressure variations per second, called Hertz (Hz). The frequency of a sound causes the tone of a sound: most aircraft are low frequencies, and most bird calls are high frequencies. A person with normal hearing can hear sounds between 20 and 20,000 Hz. The frequency range on a piano is 27.5 to 4186 Hz.

The following graphs illustrate how amplitude and frequency relate. The graphs, from recorded audio data, show the amplitude of sound as it varies across the frequency spectrum. The spectrum is divided into one-third-octave bands across the horizontal axis. The magnitude of each bar shown is the amplitude in decibels. These illustrations, and several others, are from animated slides used in the presentation to George Wright Society along with a simultaneous recording and visual display. As the recording played, each bar rose and fell independently with changes in decibel level. The left-hand graph in Figure 1 shows birds alone, and the right-hand graph shows birds and helicopters recorded at the same decibel level. The latter demonstrated to the audience that both sounds were readily distinguishable.

A sound amplitude comparison from national parks

The following comparison (Table 1) helps people relate decibel levels to what they hear. Clearly, the tone or frequency of the various sounds is different, enforcing the idea that the decibel measure doesn't fully explain sound or sound impacts.

It is fairly well accepted in the acoustic science community that a 3-decibel (dBA) dif-

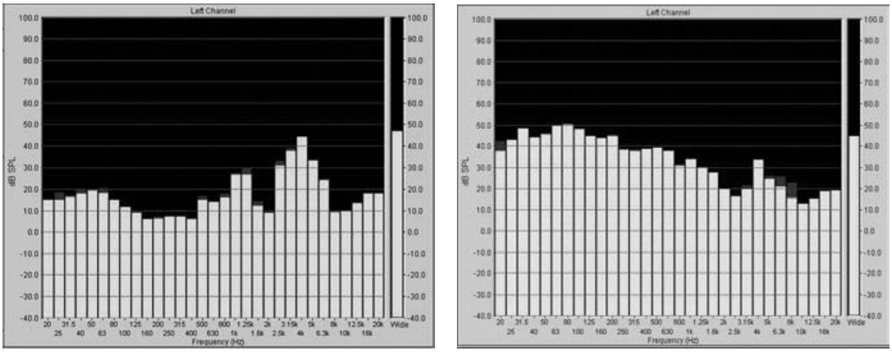


Figure 1. The relationship between amplitude and frequency. Left: birds alone, 46 dBA. Right: birds, 46 dBA, and helicopter, 46 dBA.

Sound	Sound pressure (Pa)	dBA
Threshold of human hearing	0.00002	0
Haleakala: volcano crater	0.000064	10
Canyonlands: leaves rustling	0.0002	20
Zion: crickets (at 5 m)	0.002	40
Whitman Missions: conversational speech (at 5 m)	0.02	60
Yellowstone: snowcoach (at 30 m)	0.2	80
Arches: thunder	2	100
Yukon–Charley: military jet (100 m above ground)	20	120

Table 1. Comparative decibel levels of sounds at different U.S. national park system units.

ference in sound level is perceptible to the human ear, while a 10-decibel change is a doubling of sound.

Adding sound sources together

Since decibel values are logarithmic, they are not added arithmetically. Two sources that emit sounds at 40 dB each do not produce a total sound level of 80 dB. The following example (Figure 2) shows the additive nature of sound source decibel levels.

Human hearing versus that of other species

The following graphs show the threshold of human hearing, along with those of selected birds and mammals. Different animals hear differently. This is not a biological treatise, but it should be noted that how animals hear is the product of how we have evolved in our habitats in order to feed, procreate, and survive. As an editorial note, most sound impact analyses published by federal agencies use decibels on the A-weighted scale—which is how humans hear. If it were necessary to determine sound impacts on other species, use of that scale may be appropriate for some species but not for others.

Acoustic data collected by the Natural Sounds Program

Acousticians with the Natural Sounds Program have developed protocols for data collection. Both amplitude and frequency data can be obtained and calibrated by the use of the following collection protocol (in brief):

Number of sound sources	2	2	2	4
dB of each sound:	40.0	40.0	40.0	40.0
	40.0	46.0	50.0	40.0
				40.0
				40.0
Cumulative dB:	43.0	47.0	50.4	46.0

Figure 2. The additive nature of sound source decibel levels.

- 1-second sound energy level for each of 33 one-third-octave bands (12.5 to 20,000 Hz).
- 1-second wind speed and wind direction
- Digital recording, periodic sample (usually 10 seconds every 2 or 4 minutes).
- Digital recording, events that exceed thresholds (usually 20-second recording of events that exceed 50 dB for 10 seconds)

Examples of acoustic data collected at Arches and Zion National Parks

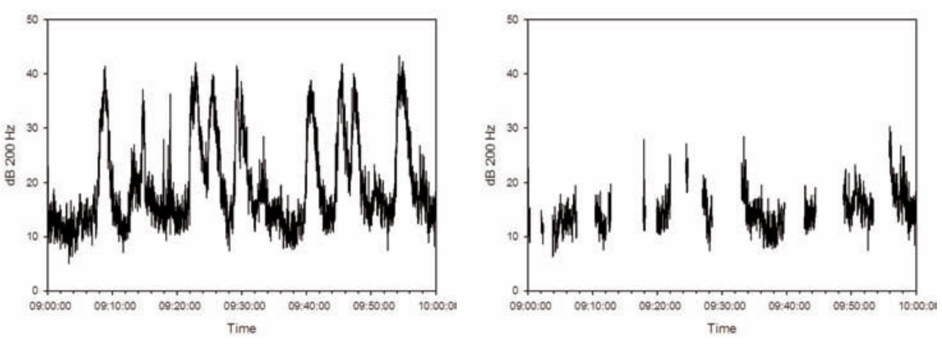
The following graphs (Figure 3) depict sonograms from data collected at Arches National Park. The sonograms capture time series data of sound events, in decibels.

From these data, several metrics may be used to characterize the soundscape as shown below. In Arches National Park on 9 October 2003, from 0900 to 1000, at the frequency of 200 Hertz, the sound level in decibels is illustrated for two conditions. These metrics display the ambient soundscape with aircraft and with aircraft sound sources removed (Table 2).

Using these data, an analysis of "noise-free interval" is produced. This analysis shows the continuous period of time during which only natural sounds are audible. In this case, aircraft were audible 53% of the hour. Most were high commercial jets measured at a maximum of 45.7 dBA during the period. However, for purposes of illustrating the overall impact, the distribution of those intervals is very revealing. For the noise-free periods of the hour, totaling about 26 minutes, the longest continuous noise-free interval was 6 minutes, 40 seconds. The average noise-free interval during the hour was just over 2 minutes (Table 3).

At Zion National Park, on the Chinle Trail, sound sources were monitored over the period of 21 August 2001 to 9 September 2001. The following graph (Figure 4) depicts, by hour of the day, the average percentage of the day in which human-related sounds were audible, distinguishing between aircraft as a source and all other sources together.

Figure 3. Sonograms for Arches National Park, 9 October 2003, 9:00–10:00 am. Left: with aircraft. Right: without aircraft.



Metric	With aircraft	Without aircraft
Total sound energy (dB)	36.8	28.5
Average level	19.6	14.7
Median level	16.7	14.2
Lowest level	5.0	6.4
Highest level	43.3	30.2

Table 2. Arches National Park, 9 October 2003, 9:00–10:00 am: the sound level in decibels under two conditions.

	Noise-free interval	Aircraft noise
Total time	0:26:32	0:33:11
Periods	12	11
Mean	0:02:13	0:03:01
Minimum	0:00:15	0:00:23
Maximum	0:06:40	0:08:15

Table 3. Arches National Park, 9 October 2003, 9:00–10:00 am: noise-free intervals.

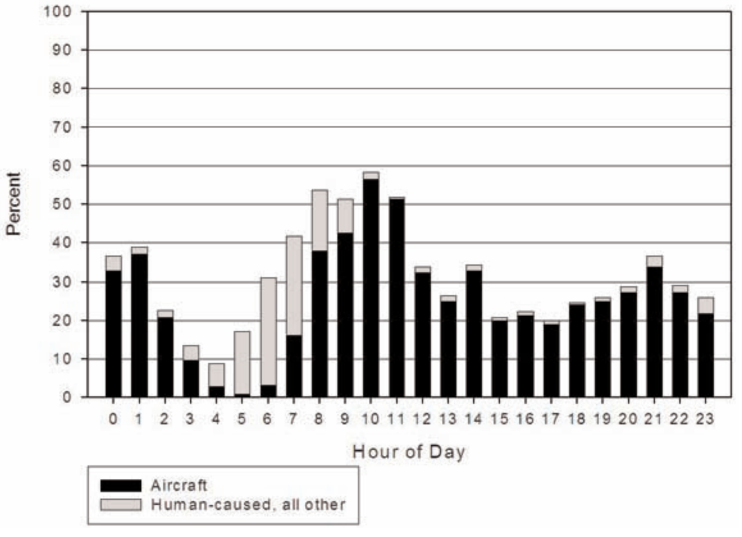


Figure 4. Average percent time audible, 21 August–9 September 2001, Chinle Trail, Zion National Park (based on 5-minute/5-second sampling scheme for entire period).

As sources were identified, their duration was timed. This is a process referred to as "audibility logging." When data are collected by automated means, the sampler periodically performs this task so that the record identifies the sources of sound being monitored in the soundscape. Without this, or without a recording to go with the data, the soundscape is characterized only by changes in decibel levels and not by what caused those changes. There would be little to distinguish between the sound of thunder and a military jet, for example. At Zion, using the referenced data set, the following "human-related" sound sources were catalogued, and the percentage of time they were heard is given. This is a further breakdown from Figure 4. Note that these are not additive percentages, because more than one source may be audible at the same time.

- Jet aircraft (55.2%)
- Propeller aircraft (24.6%)
- Helicopter (0.6%)
- Vehicle (3.6%)
- People talking (5.9%)
- Unknown motor noise (10.1%)

Soundscape management

The preceding information shows what sound is, and how it may be measured and analyzed. Soundscape management in the National Park Service uses these measures and tools for the purpose of implementing policy in order to manage the soundscape in relation to park purposes. The following concepts are important to understanding acoustics in national park soundscapes. They relate closely to the metrics that are to be used in defining standards for soundscape management.

Audibility is a measure of the biological properties of sound. It is the ability of animals with normal hearing, including humans, to hear a given sound. Of course, this is a function of the decibel level of a particular sound source through the frequency spectrum. If two dissimilar sounds (for example, a bird and an airplane) are emitted at the same time and the same decibel level, but at different frequencies, both will be heard equally well as separate tones. This frequency separation accounts for the fact that airplane sound is clearly audible even if continuous bird sounds are 8–10 decibels higher. However, if two dissimilar sounds operate at different decibel levels but at the same frequency, the louder of the two will "mask" or cover up the other.

The *natural ambient sound level* is defined as the sound condition produced by including all sounds of nature and excluding all human-related sounds. This is a convention that is important in acoustic analyses where natural or wilderness park settings are particularly of concern. The most appropriate metric for describing the natural ambient sound level is the median value in a data set that measures natural sounds alone over a period of time. The natural ambient is considered an analysis baseline, with which existing or proposed sound sources might be compared. Many park soundscapes are not naturally "quiet." Some are the "quietest" places in the United States. Usually, the higher the natural ambient sound level — for example, in the vicinity of a waterfall—the smaller the differential between the natural level and other sources of sound that may be present. Conversely, the lower the natural ambient the greater is the audibility of other sounds.

In contrast to the natural ambient is the *existing ambient sound level.* This is the composite of all sounds occurring in a given environment; it includes all natural and human-related sounds. Some agencies consider this level to be a baseline for analysis. The logic for this is not persuasive, since it could be said that this condition is always changing, and becoming higher over time.

Soundscape management indicators and standards

Standards are necessary by which to gauge whether or not management objectives are being met. They are also necessary to gauge the potential effects of a proposed action, or of

Table 4. General soundscape indicators and standards by management zone type.

Management zone	Indicator[1]	Standard
Administration and infrastructure	Percent Time Above Natural Ambient[3]	50% to 100%[2]
	Percent Time Audible[4]	50% to 100%
	Maximum Allowable Single Event dBA[5,6]	60 dBA
Frontcountry visitor use areas	Percent Time Above Natural Ambient[3]	50% to 100%[2]
	Percent Time Audible[4]	50% to 100%
	Maximum Allowable Single Event dBA[5,6]	60 dBA
Motorized travel corridors	Percent Time Above Natural Ambient[3]	50% to 100%[2]
	Percent Time Audible[4]	50% to 100%
	Maximum Allowable Single Event dBA [5,6]	60 dBA
Nonmotorized travel corridors, small backcountry and transition areas	Percent Time Above Natural Ambient[3]	20% to 40%
	Percent Time Audible[4]	10% to 35%
	Maximum Allowable Single Event dBA[5,6]	40–45 dBA
Large nonwilderness backcountry areas, RNAs (research natural areas)	Percent Time Above Natural Ambient[3]	10% to 30%
	Percent Time Audible[4]	10% to 25%
	Maximum Allowable Single Event dBA[5,6]	40-45 dBA
Designated and recommended wilderness	Percent Time Above Natural Ambient[3]	10 to 20%
	Percent Time Audible[4]	5 to 15%
	Maximum Allowable Single Event dBA[5,6]	40–45 dBA
Unique or highly sensitive areas[8]	All Indicators	Spatial/Temporal Soundscape Objectives[7]

[1] These three management standards, Time Above Natural Ambient, Percent Time Audible, and Maximum dBA, shall be achieved in 90% or more of the specific management area. Maximum sound levels are as measured at 50 ft from the source.
[2] It is understood that in some areas in some parks, non-natural sounds may be audible 100% of the time, and this may be appropriate to meet park purposes.
[3] "Time Above Ambient" means time sound levels of non-natural sounds exceed sound levels of natural sounds.
[4] "Audible" means able to be heard by a person of normal hearing.
[5] NPS has noise regulations for snowmobiles (72 dBA at 50 ft), boats (82 dBA at 82 ft), and other audio devices (60 dBA at 50 ft; as described in 36 CFR, 48 Federal Register 30275, June 30, 1983; as amended at 61 FR 46556, September 4, 1996). Natural ambient sound levels in backcountry areas of many national parks, absent mechanical or electrical sounds, are commonly between 20 dBA to 30 dBA, and often less than 20 dBA. An increase of 10 dBA is perceived as a doubling of sound level; hence, a sound level of 40 dBA would be 2 to 4 times greater than natural ambient sound levels common in national parks. Therefore a sound level of 40 dBA for mechanical/electrical sounds is suggested as a reasonable maximum allowable level in large areas managed for primitive, natural, or wilderness qualities, and where non-natural sounds are rare.
[6] Sound levels decrease as distance increases (approximately 6 dBA less as distance doubles, but dependent on several factors such as frequency content, vegetation, ground surface, temperature, humidity, and others). In general, a sound level of 78 dBA at 6 ft would be 60 dBA at 50 ft, 54 dBA at 100 ft, 30 dBA at 1,600 ft, and 18 dBA at 6,400 ft.
[7] Soundscapes in sound-sensitive areas should be managed spatially or temporally as appropriate. For example, a cultural area might be sound-sensitive year-round, or only during certain ceremonies. An example of a sound-sensitive wildlife area might be the nesting area of an endangered species during the nesting season.
[8] Unique or highly sensitive areas: This category includes areas or sites such as critical habitat, nesting sites and birthing sites for threatened and endangered species, cultural/religious/historic sites, or special designations. Often, these sites or areas are small inclusions in other management zones, even those that are zoned to frontcountry developed uses that might be inconsistent with the desired soundscape for the unique area. Special zones can be created for these, or they can be represented as a sub-zone inclusion.

the accretion of activities, on a resource. Soundscape management objectives are derived from laws, policies, and existing management plans. Indicators are selected as appropriate means by which existing or potential impacts can be measured. Standards reflect specific levels at which objectives are not met. A process for developing indicators and standards may be patterned upon the NPS visitor experience and resource protection (VERP) framework.

Generalized indicators and standards for the range of management zones found across the national park system are provided in Table 4 (previous page). Some standards are shown as a range of values. While parks are unique, it is recognized that there should be some consistency in objectives and standards for any particular type of management zone regardless of where in the system it exists—wilderness, for example. The range allows for a broad consistency while permitting flexibility for the unique circumstances that may apply within or near a park. The selected indicators and values in the Table 4 represent the current best professional judgment from the NPS Natural Sounds Program.

Acknowledgment
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