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Residual Noise Environment

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FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
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In preparing environmental impact analyses, the U.S. Air Force must address a variety of environmental issues including the noise-related effects of military operations, particularly those involving low-altitude aircraft overflights. This requires assessing the combined impacts of multiple Department of Defense (DOD) noise sources on human populations, animals and structures. Because of the variety of environments which may be impacted by DOD operations, a methodology for assessing the combined impacts of multiple noise sources associated with DOD operations must consider the various noise environments within which DOD operations occur: urban, suburban, rural, undeveloped and wilderness. Since these environments may include both natural and manmade noise sources, future modeling efforts for characterization of the total noise environment may include quantification of the residual and background noise levels, and superimposition of intrusive noises. The purpose of this report is to identify and characterize the various components comprising the residual noise level that should be considered in future modeling efforts.

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FOREWORD

This report is the second of a series of technical reports prepared under Department of the Air Force contract F33615-89-C-0574, Task 82N to develop a methodology for assessing the combined impacts of multiple environmental noise sources within the Department of Defense operating environment. Under the direction of Armstrong Laboratory/OEBN, this report was prepared by Rudy Arrieta, Connie Minish, Donal Myrick, and Larry McGlothlin of Spectrum Sciences and Software, Inc., Fort Walton Beach, Florida.

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SECTION 1 INTRODUCTION

1.1 Background

In preparing environmental impact analyses, the U.S. Air Force (USAF) must address a variety of environmental issues including the noise-related effects of military operations, particularly those involving low-altitude aircraft overflights. This requires assessing the combined impacts of multiple Department of Defense (DoD) noise sources on human populations, animals and structures in the vicinity of Military Training Routes (MTRs) and Special Use Airspace (SUA) such as Military Operations Areas (MOAs) and air-to-ground weapon ranges (Restricted Areas). Ground training operations (including operations at air-to-ground ranges) are normally conducted within areas on military reservations which are surrounded by sparsely populated (rural) or undeveloped areas. Operations in special use airspace may result in overflight of areas ranging from suburban to undeveloped. In particular, operations in MOAs and on MTRs may result in overflight of public lands managed for a variety of agricultural, natural resource extraction, and recreational uses and which may include areas designated or under consideration for management as wilderness areas. Because of the variety of environments which may be impacted by DoD operations, a methodology for assessing the combined impacts of multiple noise sources associated with DoD operations must consider the varied noise environments within which DoD operations occur. These noise environments include urban, suburban, rural, undeveloped, and wilderness areas.

Although "noise" is commonly defined as unwanted or undesirable sound, its use in this study in conjunction with a descriptive term (i.e. urban, wilderness, residual, background, etc.) is non-evaluative and carries no implication regarding the desirability or undesirability of the sound energy. In areas where the existing noise environment is dominated by a major noise source, such as aircraft noise in the vicinity of airports or motor vehicle noise in the vicinity of roadways, a variety of models are available to calculate both single event and long-term average sound levels.

In areas where no dominant noise source is present, the existing noise environment may be characterized primarily by local automotive traffic noise (EPA 1982). In such cases, population density may be used to calculate an estimated day-night average sound level (DNL). Table 1.1 provides the estimated day-night sound levels for urban and rural areas based on population density.

Table 1.1 Estimated Yearly Day-Night Average Sound Level based on population density

DESCRIPTION	POPULATION DENSITY PERSONS/SQ MI	DNL in dB
Rural (undeveloped)	20	35
Rural (partially developed)	60	40
Quiet Suburban	200	45
Normal Suburban	600	50
Urban	2,000	55
Noisy Urban	6,000	60
Very Noisy Urban	20,000	65

SOURCE: U.S. EPA 1982

NOTE: This table is for use in residential areas where there is no well-defined noise source. DNL estimates for population densities less than 1,000 persons per square mile are extrapolations.

The data in Table 1.1 is based on a relationship between DNL and population density in persons per square mile described by the following equation, where ρ represents population density:

$$L_{dn} = 10\log(\rho) + 22 \tag{1}$$

Where:

L_{dn} = *yearly Day-Night Average Sound Level (dB)*

ρ = *population density (persons/square mile)*

In general terms, urban noise environments are characterized by a moderate to high population density, with a corresponding level of transportation noise sources (including vehicle, railway and aircraft traffic), in addition to other population-related noise. As population density decreases in the suburban and rural environments, transportation and other population-related noises decrease accordingly. Although the DNL estimates for areas with a population of less than 1,000 persons per square mile listed in Table 1-1 are extrapolations, one can assume that in the absence of a dominant noise source, the yearly day-night average sound level will decrease as population density decreases. However, this relationship is unlikely to hold true in areas with very sparse populations; for example, areas with 100 or less persons per square mile (US DoD 1991). It would be expected that areas with no permanent human habitation would be characterized primarily by natural noise sources with relatively infrequent intrusions by man-made sources.

Frequently, assumptions are made that noise levels within urban, rural and wilderness noise environments may be characterized as high, medium and low, respectively. However, noise levels within any of these general noise environments may vary significantly. For example, areas with low background noise levels exist in an urban environment (such as within large parks or large tracts of undeveloped land). In contrast, in uninhabited areas such as public lands, regions of moderate or even high noise may exist. For example, on public lands managed for agricultural or natural resource production, high noise levels may be associated with agricultural, mining, or logging activities. In recreational areas, high noise levels may be associated with areas such as park entrances, parking lots, concessions, beaches and other recreational complexes, campgrounds, and locations where sightseeing aircraft operate. Even in wilderness areas, high noise levels may occur in the vicinity of rivers and waterfalls, or as a result of concentrations of animals, particularly during breeding periods (Bowlby et. al. 1990).

Since these environments may include both natural and manmade noise sources, future modelling efforts for characterization of the total noise environment may include quantification of the residual and background noise levels, and superimposition of intrusive noises. Although the residual noise level can be adequately represented by standard noise metrics, currently available techniques require noise monitoring at the specific location(s) being studied. An alternate approach is to characterize the residual and background noise levels based on specific elements that comprise the noise environment, and to develop procedures to model the noise level of these environments. This alternative would allow modelling of the total existing noise environment by adding the contribution of intrusive noise sources modeled using currently available techniques. This approach would also provide a basis for evaluating the impacts of proposed changes by adding the intrusive noise characteristics of new sources introduced by the proposed activity and deletion of the contribution of sources which may be eliminated by the action.

The purpose of this Technical Report is to identify and characterize the various components comprising the residual noise level which should be considered in future modelling efforts. The remainder of Section 1 clarifies the terminology used throughout the combined noise study effort. Section 2 discusses the metrics that may be used to characterize the residual noise environment and the underlying structure of the modelling approach. Section 3 describes the contribution of physical factors, vegetation, and animals to the residual noise environment, and identifies factors which should be considered when modelling such diverse environments.

1.2 Definitions

Much of the available literature on research related to noise environments uses similar terminology in an inconsistent manner. For example, one document may define the ambient noise level as including only natural noise sources in a wilderness environment, while another includes man-made noise sources in its definition. To avoid confusion, the terms used in this Technical Report are defined below and will be used throughout the remainder of the study effort. Accepted American National Standards Institute (ANSI) definitions have been used where possible. The source of the definition is provided when other interpretations or definitions exist.

Ambient noise is the all-encompassing noise associated with a given environment, being usually a composite of sound from many sources near and far (ANSI 1990). Since this definition differs from that used by many in the acoustical research community, the term **total noise environment** will be used instead.

Audibility, in colloquial use, is the ability of a human receiver to hear a sound, either in the presence or absence of other sounds. In acoustic terms, audibility is a continuous scalar quantity calculated as the bandwidth-corrected quotient of the means of two distributions of sound levels: one referred to as the distribution of noise alone, and one referred to as the distribution of signal plus noise. Audibility is conventionally expressed in the dimensionless unit of d' (Tabachnick et. al. 1992).

Background noise is the total noise from all sources in a system that interferes with the production, transmission, detection, measurement or recording of a signal (ANSI 1990). In practice, the background noise level is the A-weighted sound pressure level at each microphone position with the source inoperative (ANSI 1990). It contains the dominant natural sources as explained above that create the residual noise environment, plus rarer natural sources such as thunderstorms, and all nontarget man-generated sounds from transportation, construction or military activity.

L_{90} is that noise level which is exceeded 90 percent of the time (Bennett and Pearsons 1981).

Lapse rate is the rate at which air temperature changes with respect to elevation above the ground.

Natural Quiet, in colloquial use, is the sound level resulting from only naturally occurring sounds, eliminating any manmade noise sources. The following definition has been tentatively adopted by the National Park Service and the US Forest Service (Tabachnick et. al. 1992). Natural Quiet exists in the absence of non-indigenous sounds of an audibility in excess of a detectability (d') of 10 from the ambient sound environment measured over a one-minute period at a particular place (Tabachnick et. al. 1992).

Noise level is used here to signify the sound pressure level of the noise.

Ray path is the path sound takes from one point to another. It is normally not a straight path in air due to gradients of temperature and wind velocity.

Residual noise level is the fairly steady lower value of sound level upon which is superimposed discrete single events (Eldred 1975, Harris 1991).

Residual sound is the all-encompassing sound, at a specified time. It is usually a composite of sound from many sources coming from many directions, near and far, remaining at a given position in a given situation when all uniquely identifiable discrete sound sources are eliminated, rendered insignificant, or otherwise not included (Harris 1991).

Several points in this definition are worth scrutiny. It is a working definition based on what is achievable in the field. It hinges on determining when all identifiable sources of sound have been accounted for. Therefore, residual sound is produced by physical factors in the environment such as wind, local climatic factors, wind-induced vegetation noise, and, in wilderness or rural settings, animal noises (birds, amphibians, and insects such as crickets and cicadas). This definition prevents inclusion of manmade sources by virtue of these sources being discrete and identifiable almost by definition. This report focuses on the determination of this residual level and the sources that superimpose upon it to produce the total noise environment.

Sound Pressure Level is ten times the logarithm to the base 10 of the ratio of the mean-square pressure of a sound to the square of the reference sound pressure of 20 **μPa** (ANSI 1990).

SECTION 2 SYNTHESIS OF THE RESIDUAL NOISE LEVEL

2.1 Introduction

Given adequate information about the local wind velocity and direction, vegetation cover, surface water features, and precipitation, it should be possible to model the residual noise level of a specific location. A spatial model could then be developed to predict an average residual noise level for a particular time of day in a particular season for many locations in the area of interest. The probability of the presence of people or other receptors within the same area and for the same time periods can then be calculated. The residual level map can then be superimposed on this distribution for each time of day and time of year. Even in the case of wildernesses, most areas have defined trails and camping sites that can be used to create simple distributions of the probability of people being in that locality at that time. In many places, the level of resolution in the time domain will be quite limited since the residual noise level is expected to change simply with the prevailing breeze, which is determined by the local warming and cooling of air.

The data layers that are foreseen as part of a detailed analysis are enumerated below:

- Ground aspect and elevation;
- Ground albedo;
- Vegetation type;
- Probability of human presence; and
- Other sound sources that contribute to the residual noise level.

2.2 Residual Noise Analysis Metrics

In the past, the residual noise level has been reported primarily for completeness when doing community assessments of noise. In most of these cases, it has usually been assumed that the noise level exceeded 90 percent of the time (L_{90}) is an adequate approximation of the residual noise level in urban settings. In rural, undeveloped, or wilderness settings, this may not be the case since the total noise environment may be at the residual noise level most of the time with only a few events causing excursions above this level (in the desert, for instance). Dunholter et. al. (1989) used L_{90} as the background level for these environments on the basis that it seems to match as well as in an urban environment. Computer algorithms are available for generalized background and peak detection in other fields, and it may be appropriate to use these to derive the residual noise level.

2.3 Weightings

The commonly used A-frequency weighting may not be appropriate for use in determining the residual noise level. At some point in the noise analysis procedure, it is appropriate to modify the noise level to take into account the acoustical sensitivity of people or other receptors of interest. However, since the frequency components of the residual noise field have not been quantified, and quantification of this field is the purpose of this document, it is suggested that frequency weighting should not be used in determining the residual noise level. If residual noise is measured and presented in the form of a frequency spectrum, then the frequency dependence of audibility can be incorporated at appropriate points in the analysis. The original purpose of A-weighting was to develop sound level meters which could electronically simulate the response of the human ear to noise. Recent improvements in electronic instrumentation and computer based analytical techniques make it much easier to deal with detailed frequency band spectra. Once they have been correlated with a more thorough analysis that takes frequency dependance into account, the use of A-weighted metrics may be advantageous due to the wide availability of relatively inexpensive meters which provide direct A-weighted readings.

Once all the information on the residual noise level is obtained, the noise sources that are superimposed on this level must be identified. Then the sensitivity of people, animals, and structures, under different settings and at different times of day, can be taken into account. After the sources and their interaction with the environment have been quantified, the effect on people, animals and structures can be taken into account by including the following layers in a complete model:

- The Minimum Audible Field as a function of frequency;
- The sensitivity spectra of receptors (humans or animals) of concern;
- The locations, dimensions, and acoustical characteristics of structures; and
- The threshold level of the metric as a function of time.

SECTION 3 QUANTIFICATION OF THE RESIDUAL NOISE LEVEL

3.1 Introduction

The residual noise level has previously been quantified by the use of the L_{90} metric. This metric was chosen mostly out of convenience, but it does adequately represent the level above which discernible noise events occur. The residual noise level is not, however, a static quantity as it may vary several times a day. Such variation occurs because the sources comprising the residual noise level (which include nondiscrete and nonpoint sources) are strongly affected by the mesoscale climate and microclimate and their interaction with the biota of the area. The factors that affect the residual noise level, including physical features, vegetation, and animal contributions, are addressed in the following sections.

3.2 Physical Factors

Physical factors that affect the residual noise level include atmospheric attenuation, reflection and refraction, winds, water surfaces, and rain. The different sources of sound attenuation or enhancement in a locality are treated first, and then the sources of the sounds themselves are introduced and the interactions specified.

3.2.1 Atmospheric Attenuation

The attenuation of sound in air depends mainly on the frequency of the sound, the relative humidity of the air, and the temperature (Dneprovskaya et. al. 1963). The barometric pressure dependance of the atmospheric attenuation of sound is small; therefore, this source is disregarded. The atmospheric attenuation coefficient for sounds in various octave bands at various combinations of temperature and humidity is provided in Table 3-1. The value of the attenuation coefficient (alpha) obtained from the table may then be used to estimate the attenuation at a specific distance using Equation (2). It is important to note that there are various standards for the absorption of sound in air, including ANSI S1.26 (ANSI 1978, also see Harris 1966), ISO/DIS9613-1 (ISO 1990), and ARP 866 (SAE 1975). These standards are not the same,and significant variation can be found, especially at extremes of temperature and humidity.

Table 3.1 Effect of frequency, temperature, and relative humidity on atmospheric attenuation of sound

Temp. °C	RH %	Atmospheric Attenuation Coefficients (dB/km) for Specific Octave Bands					
		125	250	500	1000	2000	4000
30	10	0.96	1.8	3.4	8.7	29	96
	20	0.73	1.9	3.4	6.0	15	47
	30	0.54	1.7	3.7	6.2	12	33
	50	0.35	1.3	3.6	7.0	12	25
	70	0.26	0.96	3.1	7.4	13	23
	90	0.2	0.78	2.7	7.3	14	24
20	10	0.78	1.6	4.3	14	45	109
	20	0.71	1.4	2.6	6.5	22	74
	30	0.62	1.4	2.5	5.0	14	49
	50	0.45	1.3	2.7	4.7	9.9	29
	70	0.34	1.1	2.8	5.0	9.0	23
	90	0.27	0.97	2.7	5.3	9.1	20
10	10	0.79	2.3	7.5	22	42	57
	20	0.58	1.2	3.3	11	36	92
	30	0.55	1.1	2.3	6.8	24	77
	50	0.49	1.1	1.9	4.3	13	47
	70	0.41	1.0	1.9	3.7	9.7	33
	90	0.35	1.0	2.0	3.5	8.1	26
0	10	1.3	4.0	9.3	14	17	19
	20	0.61	1.9	6.2	18	35	47
	30	0.47	1.2	3.7	13	36	69
	50	0.41	0.82	2.1	6.8	24	71
	70	0.39	0.76	1.6	4.6	16	56
	90	0.38	0.76	1.5	3.7	12	43

SOURCE: ISO 1990

$$A_{air} = \frac{\alpha d}{1000} \tag{2}$$

Where:

A_{air} = *atmospheric attenuation (dB)*
α = *attenuation factor from Table* 3-1 *(dB/km)*
d = *distance between source and receiver (meters)*

When the path between the source and receiver is greater than 100 meters, atmospheric attenuation becomes one of the predominant effects. As an example, take the data gathered during a summer's day in 1990 in the Sierra Nevada Mountains of Central California (Sneddon et. al. 1993). The temperature by midmorning had climbed to 9 °C at a relative humidity (RH) of 80 percent (%). As can be seen from Table 3-1 (see also Beranek 1988), the attenuation factor is about 28 dB/km for sound in the octave band with a center frequency of 4000 Hz. Therefore, at a distance of 300 m, atmospheric attenuation is 8.4 dB.

As the air temperature increases to 23°C by midafternoon, the RH of the air above this spot drops below 10% to a level determined by the mixing of new air as the day's convective currents reach their maximum. If there were no contributions of water vapor from the soil, vegetation, or surrounding atmosphere, then the RH would drop to about 3%. At 4000 kHz and 23°C atmospheric attenuation is a monotonically decreasing function of RH (Beranek 1988). Using an RH value of 10% at 23°C, the resulting attenuation thus increases to 32.4 dB. This example not only represents a fairly common ocurrence, it also demonstrates that the local physical environment can have a very pronounced effect on the quality and quantity of noise (Ingard 1969; 1953). It also clearly shows that different frequency bands are selectively attenuated depending on the time of day and time of year. It is therefore anticipated that the residual noise environment will have a cyclical nature and will be a function of time of day and time of year.

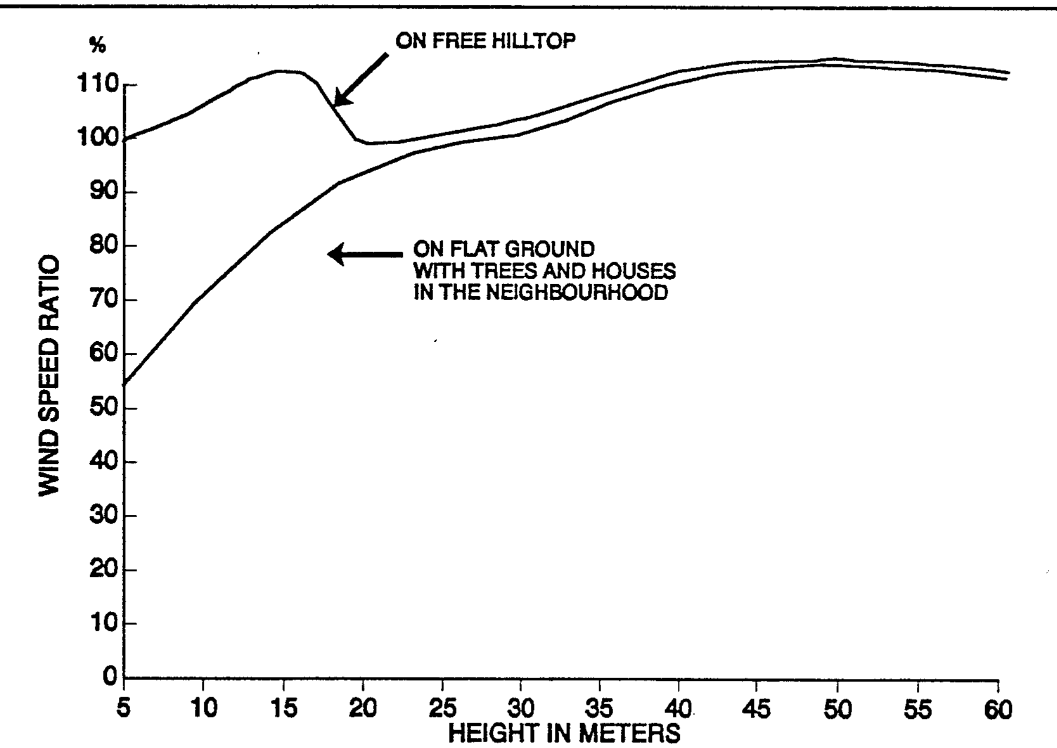
At distances greater than 100 m, significant interactions with large surfaces come into play, especially ground attenuation and reflection. Sound reflection and refraction at an interface between two sound-conducting media depend on the velocity of sound in each medium. Sound velocity is a function of the type of materials involved, their densities, temperatures, and relative velocities of the two media (Piercy and Daigle 1991).

3.2.2 Refraction and Reflection

The refraction of sound in air depends on local temperature gradients (and also on the wind gradient, which is addressed in Section 3.2.3), and on the volume of air surrounding both the noise source and the receiver. When there are large objects (several times larger than the longest wavelength of interest found in the sound) located between the source and the receiver, the reflection of sound by these objects will affect the sound energy reaching the receiver. Thus, refraction is a major factor in determining the overall attenuation of a propagated sound wave (Piercy and Daigle 1991).

3.2.3 Winds

The wind affects the residual noise level in two different ways. It produces a velocity gradient that refracts the sound (as depicted in Figure 3.1), and it also interacts with



Source: Golding 1976

Figure 3.1 Variation of wind speed with altitude over flat ground and over hill tops. The reference velocity is 5 meters above the top of the hill.

vegetation and other objects in its path to produce noise. It is the latter that we are concerned with in this section.

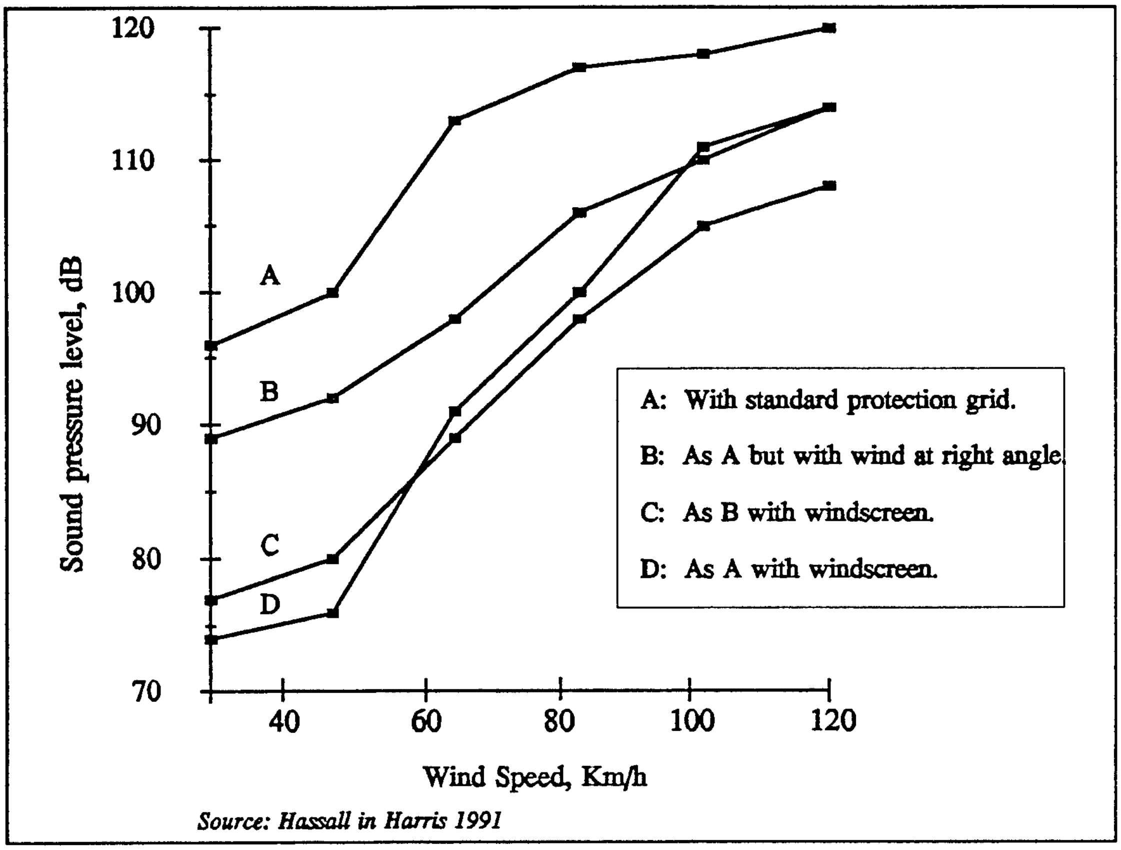


Figure 3.2 Effect of microphone orientation and shielding on measurement of wind induced noise

Figure 3.2 shows the difference in the sound produced by wind interacting with the microphone's surface, and the sound of the wind after the microphone is shielded from the wind with a wind screen (a ball made from an open-pored polyurethane foam). It illustrates two important points. First, it shows that care must be taken to prevent turbulence around the microphone from contributing to the energy detected. Second, it illustrates that considerable noise can be produced by wind alone (Hassall 1991). According to Beranek (1988), at frequencies below 100 Hz, the wind-induced noise measured in one-third octave bands is about 103 dB at 160 km/h, and decreases about 12 dB for each halving of wind velocity, whereas the levels for frequencies above 1000 Hz are about 20 dB lower. The relationship for the lower frequencies yields 55 dB at a wind speed of 20 km/h. This is about the level that would be expected from wind at this speed interacting with vegetation (Sneddon et. al. 1993). Thus wind, when present, is a major contributor to and modifier of the noise environment.

Since winds can make an important contribution to the residual noise level, specific winds are discussed below.

3.2.3.1 Sea Breeze

Solar radiation is not absorbed uniformly over the surface of the earth; rather, different areas absorb and retain heat in different amounts (Wallace and Hobs 1977; Sellers 1965). Some of this heat is eventually transferred to the air, which expands and rises over some surfaces faster than others. This differential warming and rising produces convective cells in the atmosphere. The sea breeze is an example of this effect. Since a sea breeze can reach speeds of 20 km/hr, it can be the dominant factor in determining the residual noise level. The sea breeze is part of a complete circulation cell with the sea breeze confined to the lowest kilometer of the atmosphere and a return breeze above it (Gedzelman 1980). This cell can be anywhere from 10 to 200 km wide.

The sea breeze starts a few hours after dawn, increasing into the late afternoon. At night, the breeze dies down or may even reverse direction. Thus, daily cycles are an important aspect of the sea breeze. The convection cell that leads to the sea breeze widens during the day and may lead to a sea breeze front which is a sharp demarcating line dividing two different temperature, wind, and humidity regimes. This leading edge of the sea breeze, the sea breeze front, advances inland during morning hours. Landward of the front, it is normally much hotter than shoreward of it. The transition in temperature caused by the sea breeze front can occur within a very short distance, sometimes as little as one kilometer.

The sea breeze can be affected by larger scale winds and by the Coriolis force, which changes the direction of the sea breeze in a predictable way over the course of the day.

3.2.3.2 Snow Breeze and Glacier Wind

Other breezes similar to the sea breeze can contribute to, or even dominate, the residual noise environment and which also fluctuate over the course of a day and over the course of the seasons (Budyko 1974). These include the snow breeze and the glacier wind, both of which are created by cold air from large snow fields and glaciers. These winds do not reverse direction at night, but are strongest in the afternoon when temperature differences are greatest. In these environments, these winds are often the dominant noise sources.

3.2.3.3 Valley and Canyon Winds

Another prevailing breeze is found in valleys and canyons. In this setting, large convective currents can develop depending on how steep the canyon walls are and how much solar radiation they absorb. These currents of hot air can refract sound in the valley, thus making the valley or canyon into a sound channel where sound is refracted back and forth as it travels from side to side along the valley. If the sun's rays are not too oblique, the convective cell is symmetrical with the dense air sinking in the middle of the valley. This phenomenon can be seen from the air in midmorning when fog blankets a valley floor since the sinking currents along the center of the valley dissipate fog in this area first. This type of valley circulation reverses direction during the night.

In more northerly areas, the circulation pattern changes as the valley orientation changes from north-south to east-west. The strongest convective cells are found in east-west stretches and are not symmetrical. Instead, the air flows up the south facing bluff (since it receives most of the warmth of the sun) and comes down the north facing bluff. However, in north-south stretches the sun's oblique angle may not provide enough heat to create a convective cell since first one bluff receives sunlight and then the other, weakening the heating effect. This trapping of sound generated in the canyons and possible exclusion of sound generated outside the canyon has a pronounced effect on the residual noise environment.

3.2.3.4 Mountain Winds

There are several types of mountain winds. There are winds that start after the snows have melted and the mountain absorbs the sun's rays, heating the air on slopes directly facing the sunlight. This heated air glides upslope in a layer about 100 to 200 m thick, so that within an hour after dawn a gentle breeze starts blowing up the mountain slope. This wind increases in strength through the early afternoon when it typically reaches a peak velocity of 4 to 8 knots. This rising air current often produces cumulus clouds above the mountain top. At night the wind reverses direction. It has about the same average speed as the day breeze, but it is much more gusty, with a period of 5 minutes in many places. The noise generated by this breeze has been reported to cause sleep disturbance in mountain climbers (Geiger 1965).

A mesoscale phenomenon that is similar to, but much more intense than, the nightly downslope breeze is the katabatic wind. The katabatic wind is so much stronger than the downslope breeze (in some places katabatic winds are responsible for gales of 100 knots) because its sources of cold air are extensive highland regions, glacier fields, or large continental ice sheets. As with other mountain winds, the katabatic wind is fiercest when the slope of the land is steep. The katabatic wind can be highly affected by low pressure regions around the cold highlands. Therefore, it has a yearly rather than a daily cycle. In places where the katabatic wind predominates at certain times of the year, it determines the residual noise environment.

3.2.3.5 Forest Wind

The forest wind is defined as the forest-generated flow of cooler air out of a well-shaded forest and onto adjacent open spaces. It is treated further in Section 3.3.2.

3.2.4 Surface Water Features

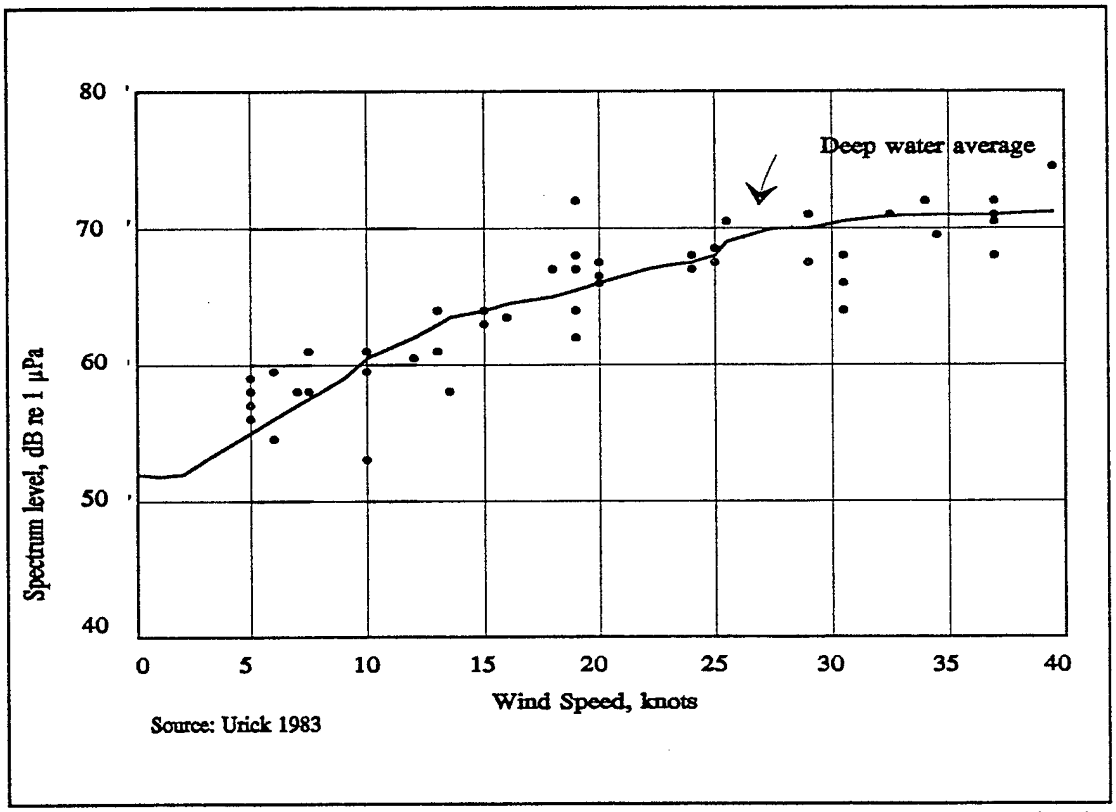


Figure 3.3 Wind-generated noise data at 1 kHz and various shallow water depths represented by dots. The curve shows deep water data.

Wind also interacts with water surfaces to produce noise. This type of noise is fairly well quantified in the literature since it interferes with the operation of sonar systems. Between 500 Hz and 20 kHz, the agitation of the local water surface is the strongest source of sonar background noise and can also be a major contributor to the residual noise level above the surface (Franz 1959). The main variable affecting this agitation is wind speed. Figure 3.3 summarizes many data sets and shows the residual noise level at 1000Hz over water for different wind speeds. The variability observed in the shallow water data is probably due to the "sea states" found when the measurements were taken. The sea state is a measure of the choppiness of the water surface and therefore depends on both the wind speed and how long it has been blowing. For any particular wind velocity an increase in the sea state increases the residual noise level. The deep water data appears to be a good approximation to the "average" levels for shallow water depths. These relationships have been well studied (Urick 1983), and can be easily included in a model of residual noise level along a shoreline.

3.2.5 Rain

Rain can significantly increase the residual noise level. Whether rain is included in the residual noise environment, however, depends on its duration and seasonal predictability. Regardless, rain can be included in a model of the natural sources of noise for a particular locality. Because it contributes to the background noise detected by sonar, considerable data is available on the sound made by rain. An increase of almost 30 dB in the 5 to 10 kHz portion of the spectrum has been noted in a heavy rain. A steady, though not torrential, rain produced an increase of 10 dB in the 19.5 kHz frequency band (Richard 1956, Clay and Medwin 1977). There are several published spectra of the noise generated by rain from measurements made in 5 meters of water in a small shallow freshwater lake (Bom 1969). The rain noise in these spectra is superimposed on very weak winds so that the wind does not appreciably contribute to the noise level. Therefore, the measured underwater spectra provides an approximation of the spectrum of the sound propagated into the air by rain falling on a water surface. The noise spectrum of rain falling on the sea surface has the properties of white noise between 1 and 10 kHz with an increase over the no-rain spectrum of 18 dB at 10 kHz. Franz (1959) developed a model based on theoretical and experimental analyses of rain drops falling on a water surface. This model was used to estimate the spectrum of rain noise that should be expected as a function of rate of rainfall. Bom (1959) found his experimental data matched Franz's model in terms of producing a flat spectrum, but his measured values were 5 to 10 dB higher, possibly because his measurements were made in a shallow lake instead of at sea and more reflection from the bottom may have occurred.

These results have to be used with caution in designing a model of rain-generated noise in air since the two media have very different properties and their interface is highly reflective to sound. Franz's theoretical development explicitly takes the medium's characteristics into account and could be used to model rain noise in air. It could therefore be included in a complete model of the residual noise environment.

3.3 Effects of Vegetation on the Residual Noise Environment

Although only attenuation is routinely taken into account, vegetation may have other effects on the residual noise environment, including vegetation-induced humidity levels of the air and the noise produced by wind rustling through vegetation. These effects are covered in the following sections.

3.3.1 Vegetative Attenuation

Attenuation due to vegetation is based on the amount of vegetation the sound wave encounters as it travels from source to receiver. When the temperature lapse rate is positive (i.e., there is an inversion) and the wind direction is from the source towards the receiver, the path of the sound wave will be an arc over the direct path from source to receiver. Due to this arcing, if the source and receiver are on level ground, the sound wave will only intersect intervening vegetation for a short distance as it propagates up and back down towards the receiver. Since these conditions are common in most localities and are stable over long periods of time, it is standard practice in the environmental noise field to consider only those "environmental conditions favorable for propagation" when calculating attenuation due to vegetation (ISO 1989). These conditions are specified as follows:

- Wind direction within an angle of 45° of the direction connecting the center of the sound source with the center of the receiver, with the wind blowing from the source to the receiver;
- Wind velocity between 1 and 5 m/s measured at a height of 3 to 11 meters above the ground; and
- Propagation (in any near horizontal direction) under a well-developed ground-based temperature inversion

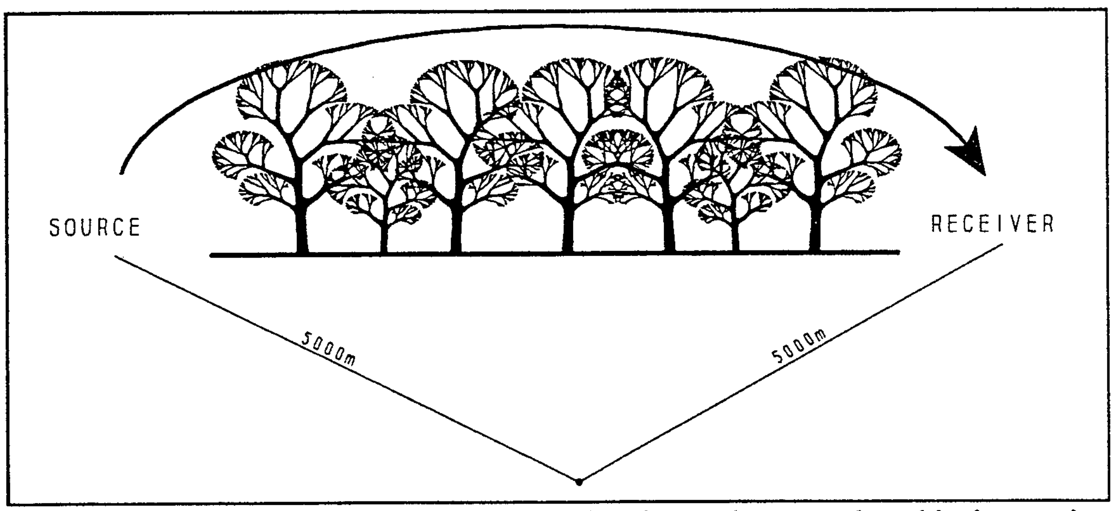
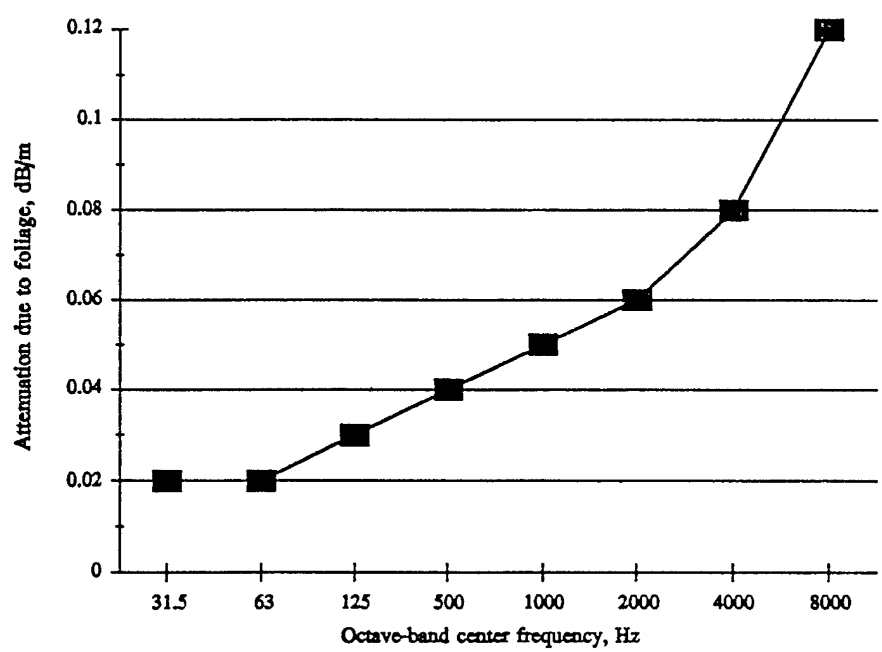


Figure 3.4 Diagram showing the arc approximation to the ray path and its interaction with vegetation.

These conditions create ray paths that can be approximated by the arc of a circle 5000 m in diameter having the source and receiver on its circumference (Figure 3.4). For standard calculations, it is assumed that the ray path will only intersect the vegetation over a distance of at most 200 meters. This method, developed by the International Organization of Standardization, uses the attenuation values shown in Figure 3.4. However, if a realistic representation of the residual noise environment is required, this approach is not sufficient since it treats all vegetation the same and makes some implicit assumptions, such as level ground.

Low frequency sound, which can propagate long distances through the ground, may be greatly attenuated by root systems, which tend to keep the soil porous (Anderson and Horonjeff 1992). Attenuation due to vegetation will be greatest, and therefore



Source: Piercy and Daigle in Harris 1991

Figure 3.5 Attenuation of sound due to propagation through vegetation.

will affect the residual noise environment the most, if the receiver is completely surrounded by forest. In this case sources internal to the forested area will be the most important in determining the residual noise environment. Insect sounds inside a forested hummock in the Everglades, for example, can be the most important source of sound in this environment (Quinn 1971).

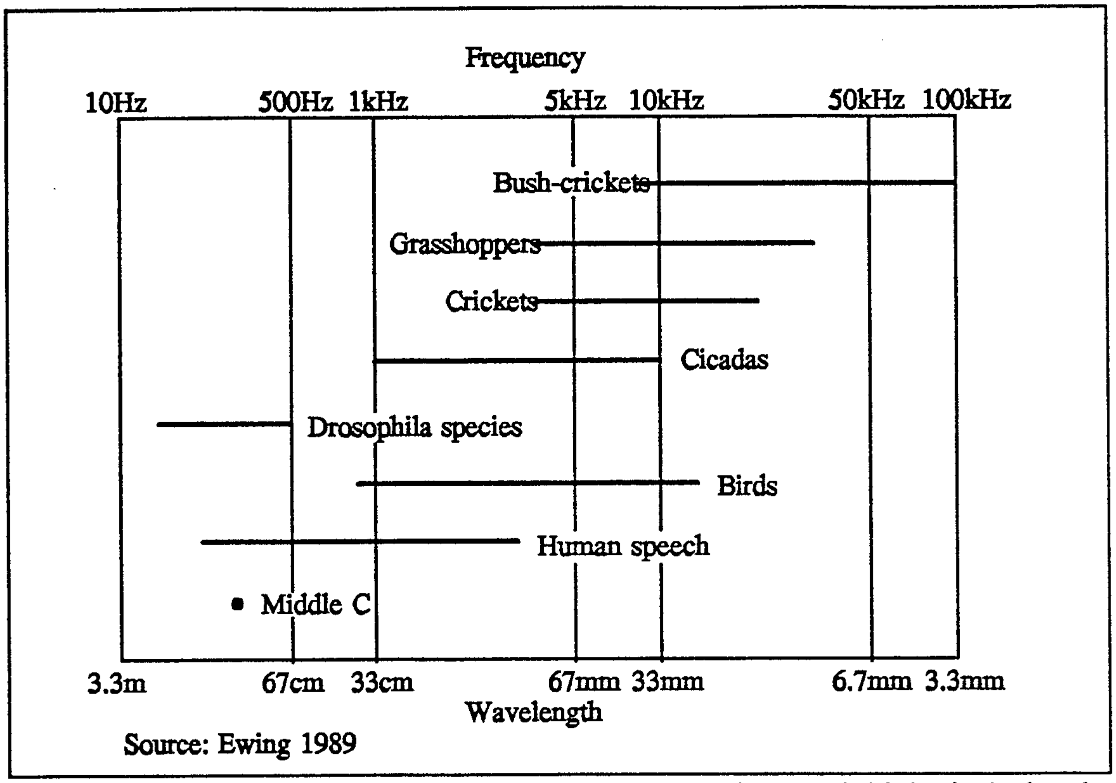


Figure 3.6 The frequency and wavelength ranges of several biological signals. Middle C is included for reference.

3.3.2 Wind Induced Sound from Vegetation

Only 0.5% of sunlight penetrates dense forests and the air under a dense forest canopy is cooler than the air above the canopy. Therefore, the lapse rate observed in open spaces does not apply within these forests. The term forest wind is defined as the forest-generated flow of cooler air out of a well-shaded forest and onto adjacent open space. It is thus similar to the sea breeze, but of a smaller scale. This wind is normally not strong (usually 2 to 3 knots) (Yoshino 1975); however, using the correlation Sneadon and coworkers (Sneddon et. al. 1993) found in the Golden Trout Wilderness between wind speed and noise coming from the treetops, a forest wind might provide a residual noise level of 45 dB. Wind speed and wind direction may be very localized, based on the geometry of forest tracts and open spaces. Therefore, wind velocity may be very different near the ground versus at a height of 10 meters, where it is usually measured. Variation in winds due to the forest wind may account for a substantial portion of the variance observed in the Golden Trout Wilderness study (Sneddon et. al. 1993).

In open woodlands or outside of closed canopy forests, the main contributor to the residual noise environment can be the interaction of near-ground winds with the local vegetation. This interaction can also change the wind velocity profile, which influences sound by refracting it back towards the ground (Monteith and Undsworth 1990). For instance, in some wilderness settings there is a strong correlation between wind speed and the A-weighted sound pressure level (averaged over 10 seconds to compensate for the time lag due to the relative positions of the anemometer and the tree tops that were the source of the sound). These data were gathered over a two hour period and a linear regression was performed using wind speed as the independent variable. Their correlation equation is as follows:

$$\text{A-Level} = 2.78(\text{wind velocity in m/s}) + 37.4\,\text{dB} \tag{3}$$

For this linear regression, $r = 0.75$. This correlation can be expected to hold in dryer climates where insects and amphibian noises should be rarer (however, even in deserts the sounds produced by amphibians can be the most significant contributor to the residual noise environment after a spring rain). It may even be possible to derive a strong correlation between the leaf area index of vegetation (loosely defined as the number of leaf surfaces intersected by a vertical ray of light on its way to the ground) and the amount of noise generated when vegetation is stimulated by a breeze. It would then be possible to use leaf area index models based on hydrologic and temperature factors (eg. Woodward 1987) to predict residual noise levels.

3.4 Animal Contributions to the Residual Noise Environment

Many animals use sound as part of courtship, territorial displays, defensive postures, or to communicate distress or other information to members of the same species. When such animals are so numerous and so persistent in their vocalizations that individual vocalizations cannot be isolated from the overall sound of the group, they contribute to the residual noise environment. The frequency and wavelength ranges of certain animal sounds are shown in Figure 3.6.

3.4.1 Insects

As shown in Figure 3.6, the frequency spectra produced by insects can vary from those produced by the common fruit fly centered at 150 Hz (See also Figure 3.7) to certain cricket courtship calls, centered around 16 kHz.

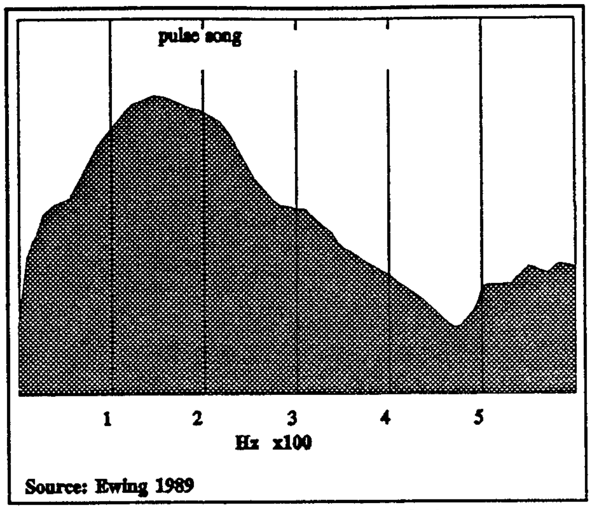


Figure 3.7 The pulse song of the common fruitfly. These flies produce some of the lowest frequency sounds of any insect.

Cicadas can significantly affect the residual noise environment of areas in eastern, southern, and western states (Borror and White 1970). Figure 3.8 depicts the frequency spectrum of the sound emitted by two species of periodical cicada (Ewing 1989). There is considerable energy in the frequency bands where humans are most sensitive (2000 to 4000 Hz), and the spectra of the two species hardly overlap. *Megacicada cassini* produces a broadband spectrum that is similar in shape to the minimum audible field curve for humans; whereas *M. septendecium* produces more energy in the low frequency range, which more closely matches the frequency range of wind-derived noise and is also the range that may mask aircraft noise.

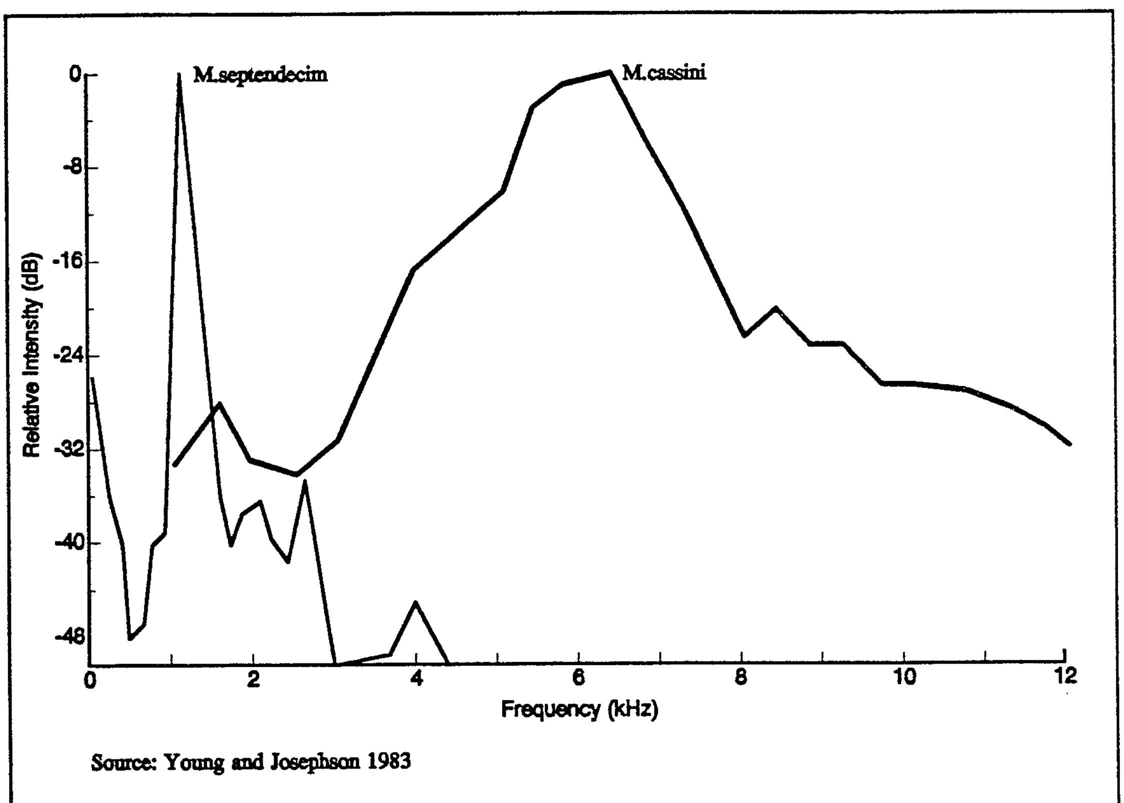


Figure 3.8 The frequency spectra of two periodical cicadas, *Magicicada septendecim* and *M. cassini.*

There are six species of periodical cicadas in the United States and one species that is not periodic. These insects emerge and mate over a period of a few months (May to September). Non-periodical cicadas, such as the Dog Day Cicada, emerge in a particular area at about the same time every year. Among periodical Cicads, individuals in different areas emerge in different years. The distribution and time of emergence of cicada broods in the United States has been mapped to help fruit growers prevent losses due to these insects. These maps could be used to predict cicada impact on the residual noise environment of a particular area.

3.4.2 Birds

Only flocking birds are thought to contribute to the residual noise environment since these birds congregate at certain times of the year and can become the loudest and largest (in physical extent) source of sound in their environment. At such times their vocalizations form the baseline din in which no one individual is discernible, and over which discrete noise events are superimposed. Knowledge of the particular roosting, nesting, loafing, or feeding sites is necessary to quantify the contribution of these populations to the residual noise environment.

Nonflocking birds can also be accounted for in a model of the residual noise environment, especially if they are territorial and the territories can be shown to be related to a particular vegetation type. For instance, male red-winged blackbirds often demarcate territories in tall marsh vegetation. In many cases, individual calls are discernible and separated in time so that a clear distinction occurs between the birds' calls and the recording baseline (or residual noise environment) over which it is superimposed.

3.4.3 Amphibians

During certain times of the year amphibians can be a constant source of noise (Conant 1975). The calls of most species are associated with the mating season for that particular species; but since amphibians are cold-blooded and most need temporary pools to mate, the start of the season differs from year to year depending on weather conditions and activities such as irrigation. Choruses are sometimes heard out of season and are made up of immature males. In some southern species, choruses can be heard throughout the year. Most treefrogs also have prolonged mating seasons that can extend for the whole summer depending on latitude. Amphibians are a very local source of sound; but in certain places, especially where wetlands are plentiful, they can contribute greatly to the residual noise environment, especially at night or after strong rains.

3.4.4 Reptiles

Very few reptiles emit sounds (Conant 1975). Some geckos emit a faint squeak, but these sounds are not expected to contribute significantly to the residual noise environment. The roar of the American alligator can be expected to contribute to the residual noise environment in places where they occur and at certain times of the year. The male produces a bellowing roar that carries for long distances and is in thhe frequency range that can mask aircraft noise (Quinn 1971, Sneddon et. al. 1993). Males also emit infrasounds by vibrating the sides of their bodies; these sounds are apparently used in courtship. The female can also roar, but with reduced intensity; she can also emit grunting noises that can be quite loud.

SECTION 4 CONCLUSIONS

4.1 Residual Noise Environment

The residual noise environment is characterized by factors that are amenable to modelling. As discussed in the preceding section, noise generated from natural sources can constitute most of the sound detected in wilderness environments. The residual noise level in this setting can be highly variable. This variability, however, is not random; it is tied to natural daily and seasonal cycles in the environment. This cyclical predictability of the natural environment results in a similar predictability in the residual noise environment. These cycles are tied to measurable parameters in the local environment such as temperature, wind speed and direction, and relative humidity. The local topography is also very important in determining the residual noise environment and this information is available from government agencies.

The biotic components of the residual noise environment are harder to quantify. However, field research on many species of interest (in terms of the contribution they make to the residual noise environment) show that both plants and animals occur in definable environments. The definition of these environments is based on the range of environmental parameters that plants and animals can tolerate, or, in the case of animals, the range of parameters they actively seek out.

These different components interact with each other to produce a highly predictable natural noise environment, encompassing both the residual noise environment and other discrete natural noise sources.

4.2 Research and Development

Many of the data layers needed for a model of the residual noise environment are already available. These include physical surface features as well as detailed atmospheric and weather records. Vegetation cover data is also available for a large part of the United States. In some instances, statistical correlations are available between these physical features and the amount of sound they produce or how much they modify noise produced elsewhere. Mathematical models have also been created and validated for underwater sound generation and propagation. At least some of these models are general enough that they could be applied to generation and propagation of sound in air. These data layers should be sufficient to support the development of a model of the residual noise environment.

For some economically significant animal species, such as cicadas, detailed maps of distribution and time of emergence are available. For most other animal species significant to the residual noise environment, general distributions are known. Life history data are available pinpointing the animals to certain locations and environments at least during their breeding seasons, which are the periods during which they are the noisiest. For each of the species of interest, good quality recordings are available which can be used to create third octave band spectra.

Much of this data can be used "as is" to develop a residual noise model. In some cases, however, the available models or data will have to be modified or processed using correlations that have to be established from field or laboratory measurements. In other cases, where the available data is incomplete, a determination must be made concerning the effort required to obtain additional data versus the adequacy of available data.

4.3 Intergovernmental Coordination

Large quantities of data have been compiled over the years regarding noise levels in the vicinity of airfields, primarily by federal agencies such as the Department of Defense, Department of Transportation, and the Environmental Protection Agency. Some of this data is identified in the references listed in Section 5. Current research efforts resulting from Public Law 100-91, known as the National Parks Overflight Act of 1987, has produced and continues to produce much data on noise levels in national parks and wilderness areas. Coordination of research efforts and sharing of data developed by the various federal agencies with interest in the noise environment should be facilitated through existing avenues, such as the Federal Interagency Committee on Noise (FICON).

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