Appendix G
Overview of Airborne and Underwater Acoustics

APPENDIX G OVERVIEW OF AIRBORNE AND UNDERWATER ACOUSTICS

G.1 INTRODUCTION

This appendix provides additional information on the characteristics of in-air noise and underwater sound. Sound transmission characteristics are different for sounds in air versus sounds in water. Similarly, sound reception sensitivities vary for in-air sound and in-water sound. Therefore, this appendix is divided into two major subsections: Airborne Noise Characteristics and Underwater Noise Characteristics. A third subsection describes sound transmission through the air-water interface. Underwater ambient sound is partially a result of sound sources that occur outside of the Hawaii Range Complex (HRC). However, for the purposes of this Environmental Impact Statement/Overseas Environmental Impact Statement (EIS/OEIS), the region of influence for underwater noise is limited to airborne and underwater sound sources that occur primarily within the HRC boundaries. Full citations for the literature cited in this appendix are provided in Chapter 9.0 of the EIS/OEIS.

G.2 AIRBORNE NOISE CHARACTERISTICS

Primary sources of Navy airborne noise in the HRC include aircraft and their weapons, naval gunfire, aerial targets, and airborne ordnance (e.g., missiles). Throughout this section, the F-4 aircraft is used to represent typical jet aircraft that operate in the HRC. For the purpose of noise characterization, aerial targets and airborne ordnance are essentially small-scale aircraft.

Two distinct types of noise may result from aircraft activities. When an aircraft flies slower than the speed of sound or subsonically, noise is produced by the aircraft's engine and by effects of aircraft movement through air. When an aircraft flies faster than the speed of sound, a sharply defined shock front is created, producing a distinct phenomenon called "overpressure." Noise produced by this physical phenomenon is termed "impulse noise." Thunder claps, noise from explosions, and sonic booms are examples of impulse noise. Airborne noise that originates in higher altitudes is seldom heard on the ground. This is due to the upward bending of sound that takes place in temperature inversions, where the surface temperature is warmer than the temperature at the higher altitude of the sound source. The characteristics of subsonic and supersonic noise are discussed below.

G.2.1 SUBSONIC NOISE

The physical characteristics of noise (or sound) include its intensity, frequency, and duration. Sound is created by acoustic energy, which produces pressure waves that travel through a medium, such as air or water, and are sensed by the eardrum. This may be likened to ripples in water that would be produced when a stone is dropped into it. As acoustic energy increases, the intensity or height of these pressure waves increases, and the ear senses louder noise. The ear is capable of responding to an enormous range of sound levels, from that of a soft whisper to the roar of a rocket engine.

Units of Measurement

The range of sound levels that humans are capable of hearing is very large. If the faintest sound level we can recognize (threshold of hearing) is assigned a value of one, then the highest level humans are capable of hearing (threshold of pain), measured on the same scale, would have a value of 10 million. In order to make this large range of values more meaningful, a logarithmic mathematical scale is used: the decibel [dB] scale. On this scale, the lowest level audible to humans is 0 dB and the threshold of pain is approximately 140 dB. The reference level for the decibel scale used to describe airborne sound is thus the threshold of hearing (for young adults). In physical terms, this corresponds to a sound pressure of 20 micropascals (μPa). Atmospheric pressure is about 100,000 pascals (Pa).

Noise Measurement (weighting)

The normal human ear can detect sounds that range in frequency from about 20 cycles per second or hertz (Hz) to 15,000 Hz. However, all sounds throughout this range are not heard equally well. Figure G-1 shows the in-air hearing threshold curves (audiograms) for humans and a marine mammal species that can hear well in air as well as underwater. The human ear can be seen to be most sensitive at 1 to 4 kilohertz (kHz), whereas the sensitive band for the elephant seal extends upward to at least 10 kHz. However, at most frequencies the hearing threshold for these animals listening in air is 20 to 50 dB higher (less sensitive) than that for the human.

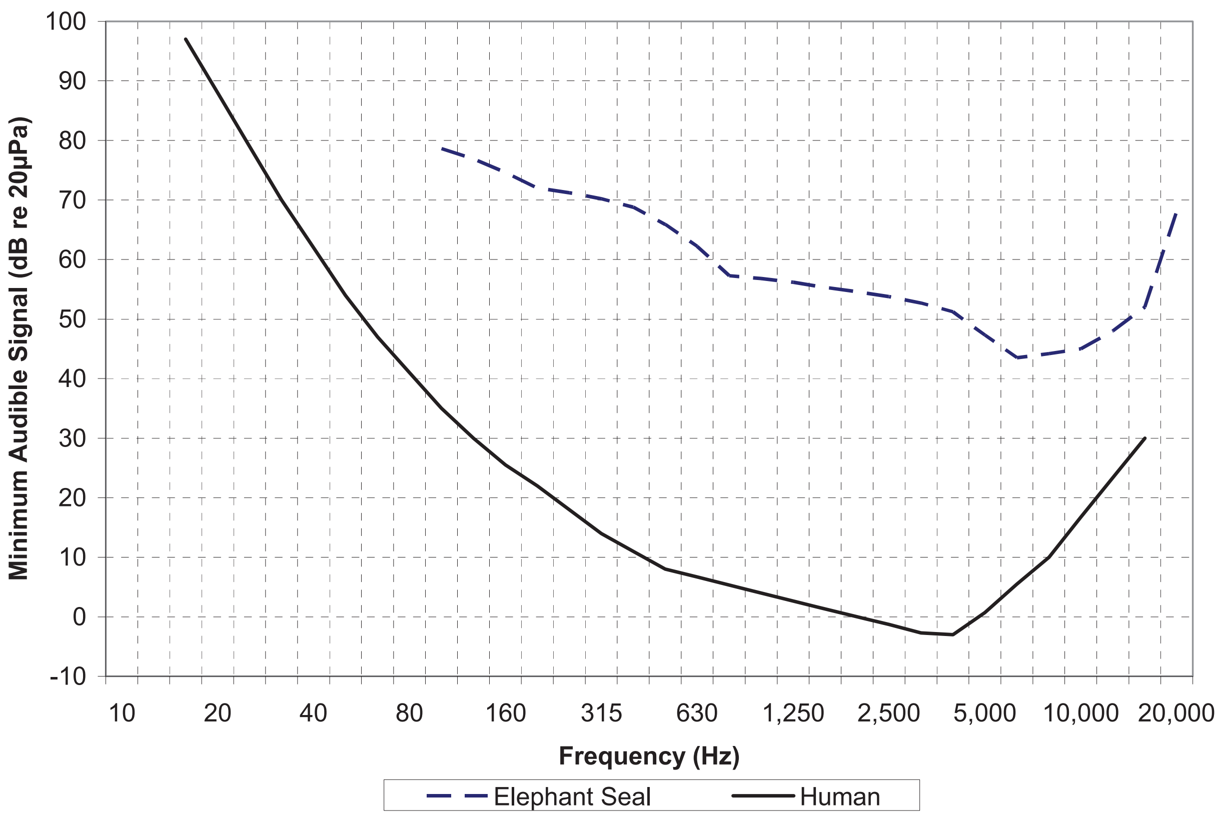


Figure G-1. Human and Marine Mammal In-Air Hearing Thresholds

Sound level meters have been developed to measure sound fields and to show the sound level as a number proportional to the overall sound pressure as measured on the logarithmic scale described previously. This is called the sound pressure level (SPL). It is often useful to have this meter provide a number that is directly related to the human sensation of loudness. Therefore, some sound meters are calibrated to emphasize frequencies in the 1 to 4 kHz range and to de-emphasize higher and especially lower frequencies to which humans are less sensitive. Sound level measurements obtained with these instruments are termed "A-weighted" (expressed in dBA). The A-weighting function is shown in Figure G-2. It is closely related to the human hearing characteristic shown previously in Figure G-1. Because other animals are sensitive to a different range of frequencies, other weighting protocols may be more appropriate when their specific hearing characteristics are known. Alternative measurement procedures such as C-weighting or flat-weighting (unweighted), which do not de-emphasize lower frequencies, may be more appropriate for various animal species such as baleen whales.

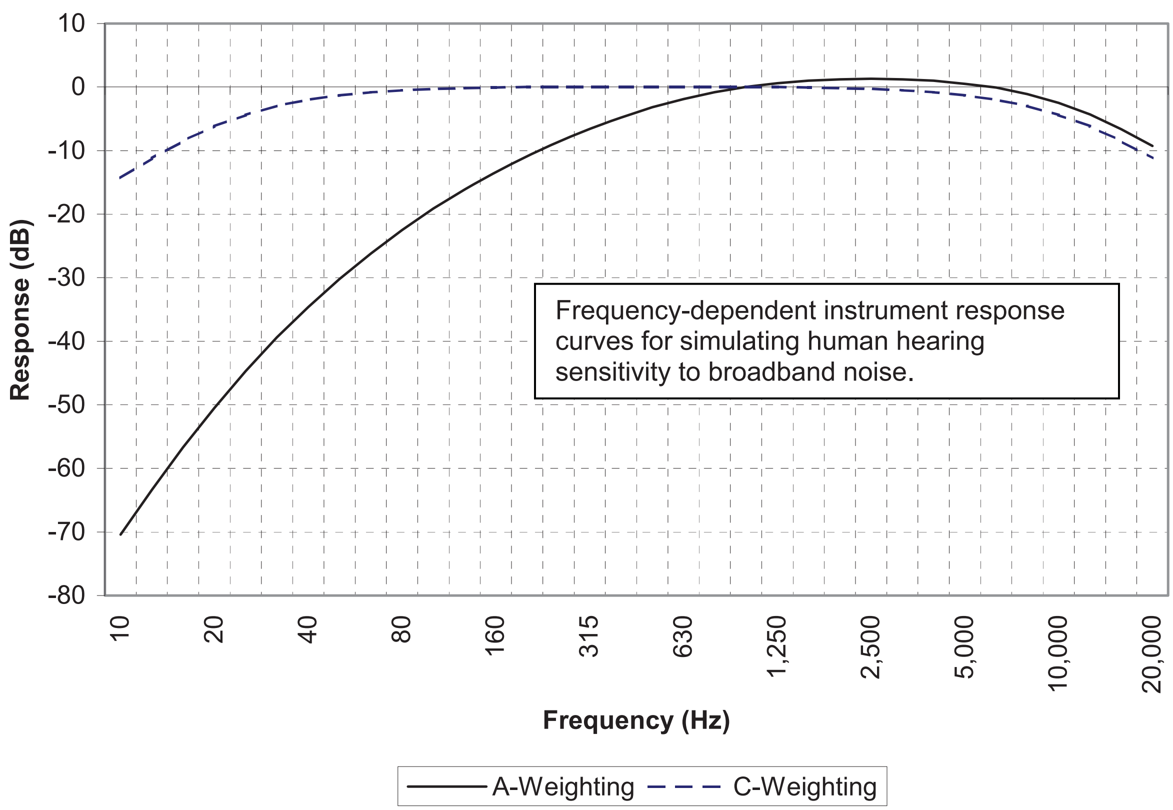


Figure G-2. Noise Weighting Characteristics

Although sound is often measured with instruments that record instantaneous sound levels in dB, the duration of a noise event and the number of times noise events occur are also important considerations in assessing noise impacts. With these measurements, sound levels for individual noise events and average sound levels, in decibels, over extended periods of hours, days, months, or years can be calculated (e.g., the daily day-night average sound level [L_{dn}] in dB).

Sound Exposure Level (Single Noise Event)

The sound exposure level (SEL) measurement provides a means of describing a single, time varying, noise event. It is useful for quantifying events such as an aircraft overflight, which includes the approach when noise levels are increasing, the instant when the aircraft is directly overhead with maximum noise level, and the period of time while the aircraft moves away with decreasing noise levels. SEL is a measure of the physical energy of a noise event, taking into account both intensity (loudness) and duration. SEL is based on the sounds received during the period while the level is above a specified threshold that is at least 10 dB below the maximum value measured during a noise event. SEL is usually determined on an A-weighted basis, and is defined as the constant sound level that provides the same amount of acoustic exposure in one second as the actual time-varying level for the exposure duration. It can also be expressed as the 1-second averaged equivalent sound level (L_{eq} 1 sec).

Table G-1 provides a brief comparison of A-weighted, C-weighted, and flat SEL (F-SEL) values for military aircraft operating at various altitudes and power settings. By definition, SEL values are normalized to a reference time of one second and should not be confused with either the average or maximum noise levels associated with a specific event. There is no general relationship between the SEL value and the maximum decibel level measured during a noise event. By definition, SEL values exceed the maximum decibel level where noise events have durations greater than 1 second. For subsonic aircraft overflights, maximum noise levels are typically 5 to 7 dB below SEL values.

Table G-1. SEL Comparison for Select Department of Defense Aircraft (in dB)

	P-3			F-4C			F/A-18		
Power Setting	2000 ESHP			100% RPM			88% RPM		
Speed (knots)	180			300			400		
Sound Exposure Level (SEL) at Ground Level									
Altitude	**A-SEL**	**C-SEL**	**F-SEL**	**A-SEL**	**C-SEL**	**F-SEL**	**A-SEL**	**C-SEL**	**F-SEL**
2,500 feet	83.5	88.4	88.4	106.7	110.6	110.4	91.3	95.3	95.2
2,000 feet	85.6	90.0	90.0	109.0	112.7	112.6	93.7	97.4	97.3
1,600 feet	87.7	91.6	91.6	111.3	114.8	114.6	96.0	99.4	99.4
1,000 feet	91.7	94.7	94.7	115.7	118.7	118.7	100.2	103.2	103.2
500 feet	97.2	99.2	99.3	122.3	124.1	124.3	105.9	108.5	108.5
315 feet	100.6	102.2	102.2	126.7	127.5	127.7	109.3	111.7	111.8
200 feet	103.9	105.1	105.2	130.9	130.6	130.9	112.5	114.8	114.9

ESHP = effective shaft horsepower
RPM = revolutions per minute

Day-Night Average Sound Level

The day-night average sound level (L_{dn} or DNL) is the energy-averaged sound level measured over a 24-hour period, with a 10 dB penalty assigned to noise events occurring between 10:00 p.m. and 7:00 a.m. L_{dn} values are obtained by summation and averaging of SEL values for a given 24-hour period. L_{dn} is the preferred noise metric of the U.S. Department of Housing and Urban Development, Federal Aviation Administration, U.S. Environmental Protection Agency, and Department of Defense insofar as potential effects of airborne sound on humans are concerned.

People are constantly exposed to noise. Most people are exposed to average sound levels of 50 to 55 L_{dn} or higher for extended periods on a daily basis. Normal conversational speaking produces received sound levels of approximately 60 dBA. Studies specifically conducted to determine noise impacts on various human activities show that about 90 percent of the population is not significantly bothered by outdoor average sound levels below 65 L_{dn} (Federal Aviation Administration, 1985).

L_{dn} considers noise levels of individual events that occur during a given period, the number of events, and the times (day or night) at which events occur. Since noise is measured on a logarithmic scale, louder noise events dominate the average. To illustrate this, consider a case in which only one aircraft flyover occurs in daytime during a 24-hour period, and creates a sound level of 100 dB for 30 seconds. During the remaining 23 hours, 59 minutes, and 30 seconds of the day, the ambient sound level is 50 dB. The calculated sound level for this 24-hour period is 65.5 L_{dn}. To continue the example, assume that 10 such overflights occur during daytime hours during the next 24-hour period, with the same 50 dB ambient sound level during the remaining 23 hours and 55 minutes. The calculated sound level for this 24-hour period is 75.4 L_{dn}. Clearly, the averaging of noise over a given period does not suppress the louder single events.

In calculating L_{dn}, noise associated with aircraft activities is considered, and a 10 dB penalty is added to activities that occur between 10:00 p.m. and 7:00 a.m.; this time period is considered nighttime for the purposes of noise modeling. The 10 dB penalty is intended to compensate for generally lower background noise levels and increased human annoyance associated with noise events occurring between the hours of 10:00 p.m. and 7:00 a.m.

While L_{dn} does provide a single measure of overall noise, it does not provide specific information on the number of noise events or specific individual sound levels that occur. For example, as explained above, an L_{dn} of 65 dB could result from very few, but very loud events, or a large number of quieter events. Although it does not represent the sound level heard at any one particular time, it does represent total sound exposure. Scientific studies and social surveys have found L_{dn} to be the best measure to assess levels of human annoyance associated with all types of environmental noise. Therefore, its use is endorsed by the scientific community and governmental agencies (U.S. Environmental Protection Agency, 1974; Federal Interagency Committee on Urban Noise, 1980; Federal Interagency Committee on Noise, 1992).

Onset-Rate Adjusted Day-Night Average Sound Level

Aircraft operating at low altitude and in special use airspace generate noise levels different from other community noise environments. Overflights can be sporadic, which differs from most community environments where noise tends to be continuous or patterned.

Military overflight events also differ from typical community noise events because of the low altitude and high airspeed characteristics of military aircraft. These characteristics can result in a rate of increase in sound level (onset rate) of up to 30 dB per second. To account for the random and often sporadic nature of military flight activities, computer programs calculate noise levels created by these activities based on a monthly, rather than a daily, period. The L_{dn} metric is adjusted to account for the surprise, or startle effect, of the onset rate of aircraft noise on humans. Onset rates above 30 dB per second require an 11 dB penalty because they may cause a startle associated with the rapid noise increase. Onset rates from 15 to 30 dB per second require an adjustment of 0 to 11 dB. Onset rates below 15 dB per second require no adjustment because no startle is likely. The adjusted L_{dn} is designated as onset-rate adjusted monthly day-night average sound level (L_{dnmr}).

G.2.2 SUPERSONIC NOISE

A sonic boom is the noise a person, animal, or structure on the earth's surface receives when an aircraft or other type of air vehicle flies overhead faster than the speed of sound (or supersonic). The speed of sound is referred to as Mach 1. This term, instead of a specific velocity, is used because the speed at which sound travels varies for different temperatures and pressures. For example, the speed of sound in air at standard atmospheric conditions at sea level is about 772 statute miles per hour, or 1,132 feet (ft) per second. However, at an altitude of 25,000 ft, with its associated lower temperature and pressure, the speed of sound is reduced to 1,042 ft per second (approximately 710 miles per hour). Thus, regardless of the absolute speed of the aircraft, when it reaches the speed of sound in the environment in which it is flying, its speed is Mach 1.

Air reacts like a fluid to supersonic objects. When an aircraft exceeds Mach 1, air molecules are pushed aside with great force, forming a shock front much like a boat creates a bow wave. All aircraft generate two shock fronts. One is immediately in front of the aircraft; the other is immediately behind it. These shock fronts "push" a sharply defined surge in air pressure in front of them. When the shock fronts reach the ground, the result is a sonic boom. Actually, a sonic boom involves two very closely spaced impulses, one associated with each shock front. Most people on the ground cannot distinguish between the two and they are usually heard as a single sonic boom. However, the paired sonic booms created by vehicles the size and mass of the space shuttles are very distinguishable, and two distinct booms are easily heard.

Sonic booms differ from most other sounds because: (1) they are impulsive; (2) there is no warning of their impending occurrence; and (3) the peak levels of a sonic boom are higher than those for most other types of outdoor noise. Although air vehicles exceeding Mach 1 always create a sonic boom, not all sonic booms are heard on the ground. As altitude increases, air temperature normally decreases and these layers of temperature change cause the shock front to be turned upward as it travels toward the ground. Depending on the altitude of the aircraft and the Mach number, the shock fronts of many sonic booms are bent upward sufficiently that they never reach the ground. This same phenomenon also acts to limit the width (area covered) of those sonic booms that actually do reach the ground.

Sonic booms are sensed by the human ear as an impulsive (sudden or sharp) sound because they are caused by a sudden change in air pressure. The change in air pressure associated with a sonic boom is generally a few pounds per square foot, which is about the same pressure change experienced riding an elevator down two or three floors. It is the rate of change—the sudden onset of the pressure change—that makes the sonic boom audible. The air pressure in excess of normal atmospheric pressure is referred to as “overpressure.” It is quantified on the ground by measuring the peak overpressure in pounds per square foot and the duration of the boom in milliseconds. The overpressure sensed is a function of the distance of the aircraft from the observer; the shape, weight, speed, and altitude of the aircraft; local atmospheric conditions; and location of the flight path relative to the surface. The maximum overpressures normally occur directly under the flight track of the aircraft and decrease as the slant range, or distance, from the aircraft to the receptor increases. Supersonic flights for a given aircraft type at high altitudes typically create sonic booms that have low overpressures but cover wide areas if the sonic boom reaches the ground.

The noise associated with sonic booms is measured on a C-weighted scale (as shown previously in Figure G-2). C-weighting provides less attenuation at low frequencies than A-weighting. This is appropriate based on the human auditory response to the low-frequency sound pressures associated with high-energy impulses (such as those generated by sonic booms).

G.2.3 AIRBORNE NOISE EFFECTS ON WILDLIFE

The previous discussion primarily concerned the metrics that have been developed to predict human response to various noise spectral and temporal characteristics. Response prediction metrics for non-human species such as marine mammals are generally not available. Because of the limited amount of response data available for marine mammals, it is not possible to develop total sound exposure metrics similar to those applied to human population centers. Instead, the potential impacts of noise sources in the HRC need to be assessed by examining individual source-receiver encounter scenarios typical of range activities. Assessment of potential effects must consider both airborne noise on marine mammals out of the water (e.g., pinniped), and airborne noise (transmitted into the water) potentially effecting marine mammals when they are underwater (e.g., cetacea).

There have been several studies of hauled-out pinniped response to airborne noise and sonic booms from aircraft and missile flyovers, although few sound exposure data have been reported. For marine mammals underwater, one study—the Malme et al. (1984) investigation of gray whales—is the only study to provide data on reactions to aircraft sound underwater that was isolated from other potential stimuli such as visual behavioral reactions elicited from low altitude aircraft. As demonstrated by that study, the underwater received levels necessary to elicit reactions (115 dB to 127 dB SPL) would require an airborne source level at the surface of approximately 175 dB to 187 dB. This is much higher than should be expected as a result of most aircraft overflight in the HRC for reasons described later in Section G.3 involving sound transmission through the air-water interface. To assess the potential impact of airborne noise sources in the HRC on non-human species, a weighting function related to the hearing characteristics of a specific species is required, analogous to the A-weighting used for human response prediction (see Southall et al., 2007).This facilitates the application of sound level criteria based on potential avoidance behavior, potential temporary threshold shift, or some other appropriate response (refer to Section 4.1 of the EIS/OEIS, Marine Mammals).

If the hearing thresholds of a species have been measured at various frequencies, as in Figure G-1, the resulting audiogram can be used as a weighting function. An example of this is shown in Figure G-3 where the 1/3-octave spectra of two different types of aircraft are shown. (Sound levels are shown in 1/3-octave bands because in humans and some mammals, the effective filter bandwidth of the hearing process is not constant but has a proportional bandwidth of approximately 1/3-octave.) The F-4 jet noise spectrum is seen to be dominated by frequencies above 500 Hz, whereas the P-3 has dominant propeller noise bands at 63 and 125 Hz. When these radiated noise spectra are weighted by subtracting the elephant seal hearing response (see Figure G-1), the effective perceived level spectra are obtained. The difference in perceived loudness of these two aircraft, as heard by the seal, can be estimated by looking at the overall perceived levels (shown on the right edge of the graph). There is a difference of about 30 dB in the overall perceived levels even though there is only a difference of about 10 dB in the overall flat-weighted levels. Human listeners perceive a 10-dB difference in sound level as being approximately a factor of two. If the seal has a similar perception, the two aircraft would differ in perceived loudness by about eight times, but the measured difference for a flat sound level meter would be only 10 dB.

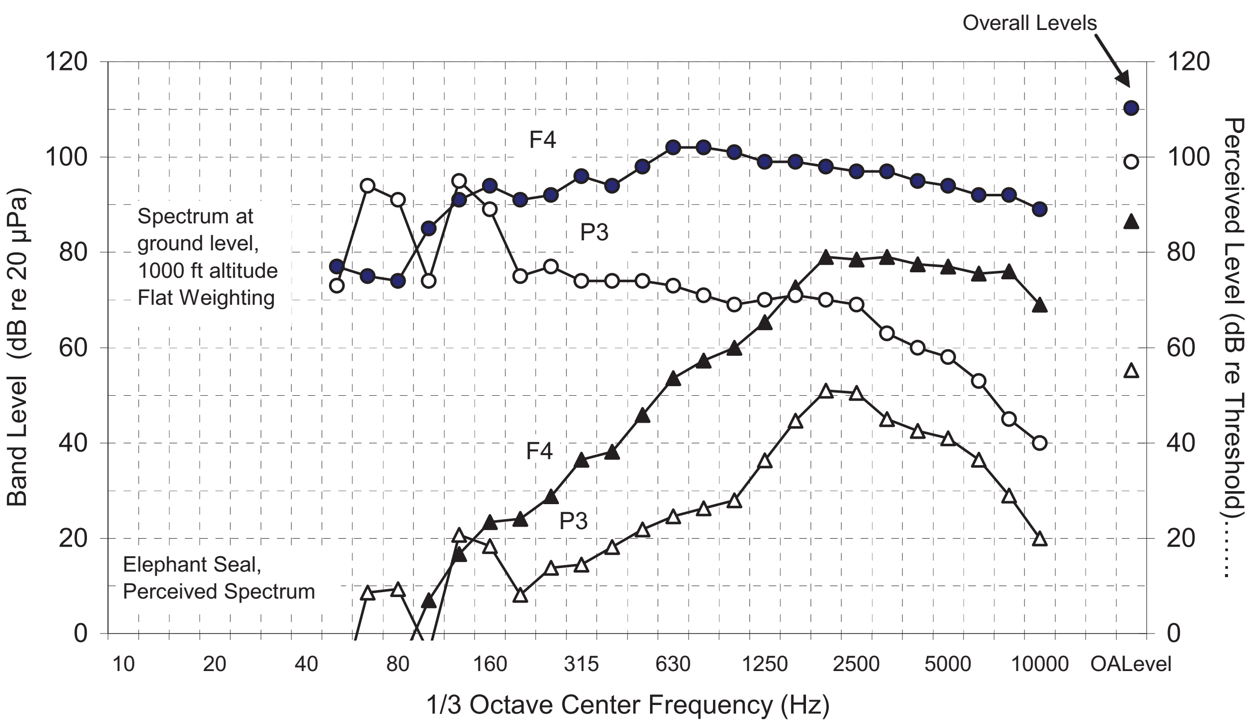


Figure G-3. Aircraft Noise Spectra vs. Hearing Response

While the actual audiogram can be used as a weighting function as demonstrated above, this is not a practical solution in the present application because of the large number of species and sources involved. Moreover, the audiograms of many animal species listening in air are not known. Several species of concern, such as pinnipeds and birds, have reduced sensitivity at low frequencies as compared with at moderate frequencies (the same pattern as in humans). Therefore, the A-weighting response appropriate for humans was examined as a potential basis for estimating the levels perceived by species exposed to a variety of noise sources on the HRC.

For birds, a comparison of real and perceived levels from F-4 and P-3 aircraft was made by using the reported hearing thresholds of selected bird species. The results of the analysis show that the measured difference in overall received noise levels for the two aircraft produced by the A-weighting function is comparable to the estimated differences in perceived levels for birds (Table G-2). The measured difference using unweighted overall sound levels is much smaller and thus would provide a poor estimate of the potential noise impact of these sources on birds. This comparison indicated that A-weighting (which attenuates low frequencies) is effective in simulating the hearing function of birds, since the difference in the A-weighted aircraft spectra is similar to the difference in the perceived levels. A-weighted metrics are therefore considered appropriate for use in determining potential noise impacts on birds.

Table G-2. Analysis of A-Weighted Sound Level vs. Flat Overall Level as a Measure of Loudness for Birds

	Overall Measured Sound Level (1,000 feet altitude, re 20 μPa)		Perceived Sound Level [3] (Received level—hearing threshold)	
Aircraft	**dB (flat) [1]**	**dBA [2]**	**Anseriforms [4]**	**Passeriforms [5]**
F-4 (100%)	110.0	109.0	94.0	87.0
P-3 (100%)	99.0	84.0	65.0	59.0
F-4 - P-3 difference	11.0	25.0	29.0	28.0

Notes:

[1] dB (flat) - overall sound level with no weighting.

[2] dBA - overall A-weighted level.

[3] Perceived Sound Level - overall sound level of the aircraft above the hearing threshold. It is an estimate of the loudness perceived by a given species.

The difference between the unweighted levels of the two aircraft is 11 dB, whereas the A-weighted level difference is 25 dB. The F-4 has a significant amount of sound energy at high frequencies compared with the P-3. If A-weighting (which attenuates low frequencies) is effective in simulating the hearing function of birds, the difference in the A-weighted aircraft spectra should be similar to the difference in perceived levels, as these data indicate.

[4] Anseriforms are waterfowl (e.g., ducks, geese, swans).

[5] Passeriforms are perching birds or passerines (i.e., songbirds).

The hearing response of the elephant seal in its most sensitive range is about 20 dB less sensitive than that of human hearing (see Figure G-1). To compensate for this, an additional 20 dB attenuation was added to the A-weighting response and the resulting characteristic was applied to the F-4 and P-3 spectra. The results are shown in Figure G-4. Here the adjusted A-weighted responses are compared to the estimated perceived responses. The overall adjusted A-weighting responses for the two aircraft can be seen to differ by about 26 dB, compared to the perceived difference of about 30 dB. The overall adjusted A-weighted level exceeds the overall perceived level by about 4 dB for the F-4 and about 9 dB for the P-3. This difference occurs because, at low frequencies, the A-weighting factors are relatively higher than the seal audiogram. This difference is most important for sources with dominant low-frequency components.

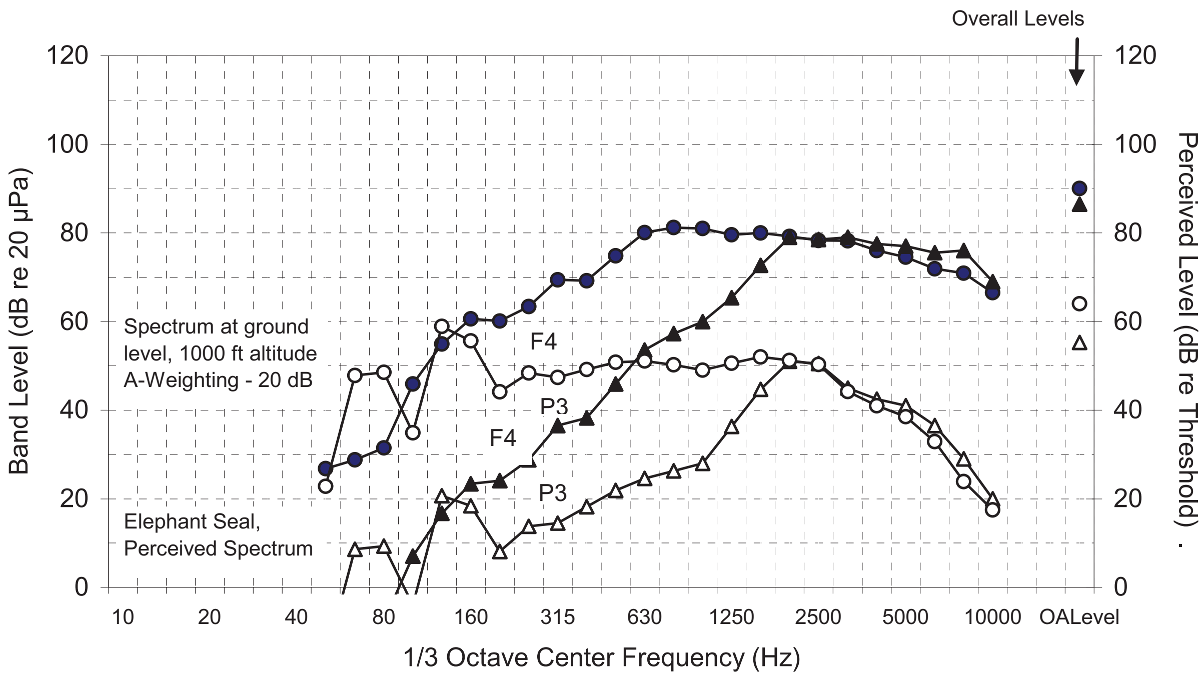


Figure G-4. Adjusted A-Weighting of Aircraft Noise vs. Hearing Response

G.2.4 AMBIENT NOISE

Ambient noise is the background noise at a given location. Airborne ambient noise can vary considerably depending on location and other factors, such as wind speed, temperature stratification, terrain features, vegetation, and the presence of distant natural or man-made noise sources.

In predicting human response to loud airborne noise sources, it is reasonable to assume that ambient background noise would have little or no effect on the calculated noise levels since the ambient levels would add insignificant fractions to calculated values. Therefore, ambient background noise is not considered in the noise calculations.

Ambient noise may have a more significant effect on prediction of marine mammal response to loud airborne noise sources. Marine mammals are exposed to a wide range of ambient sounds ranging from the loud noise of nearby wave impacts on the quiet of remote areas during calm wind conditions. The ambient noise background on beaches is strongly influenced by surf noise. During high surf conditions pinnipeds may not hear an approaching aircraft until it is nearly overhead. The resulting rapid noise level increase may cause a panic response that normally would not occur for calm conditions when the approaching aircraft can be initially heard at longer ranges. Some examples of airborne noise levels in human and marine mammal habitat are given in Table G-3.

It should be noted that the characteristics of subsonic noise, which is measured on an A-weighted scale, and supersonic noise, which is measured on a C-weighted scale, are different. Therefore, each is calculated separately, and it would be incorrect to add the two values together. Nevertheless, both subsonic and supersonic noises occur in the HRC. Together, they form the cumulative acoustic environment in the region. Therefore, each is addressed where applicable in this EIS/OEIS.

Table G-3. Representative Airborne Noise Levels

Source of Noise	dBA re 20 μPa
F/A-18 at 1,000 feet (Cruise Power)	98
Helicopter at 200 feet (UH-1N)	91
Car at 25 feet (60 mph) [1]	70–80
Light Traffic at 100 feet [1]	50–60
Quiet Residential (daytime) [1]	40–50
Quiet Residential (night) [1]	30–40
Wilderness Area [1]	20–30
Offshore (low sea state) [2]	40–50
Surf [2]	60–70

[1] Kinsler et al., 1982.
[2] U.S. Coast Guard, 1960.

G.3 SOUND TRANSMISSION THROUGH THE AIR-WATER INTERFACE

Many of the sound sources considered in this EIS/OEIS are airborne vehicles, but a significant portion of the concern about noise impacts involves marine animals at or below the surface of the water. Thus, transmission of airborne sound into the ocean is a consideration. This subsection describes some basic characteristics of air-to-water transmission of sound for both subsonic and supersonic sources. Sound is transmitted from an airborne source to a receiver underwater by four principal means: (1) a direct path, refracted upon passing through the air-water interface; (2) direct-refracted paths reflected from the bottom in shallow water; (3) lateral (evanescent) transmission through the interface from the airborne sound field directly above; and (4) scattering from interface roughness due to wave motion.

Several papers are available in the literature concerning transmission of sound from air into water. Urick (1972) presents a discussion of the effect and reports data showing the difference in the underwater signature of an aircraft overflight for deep and shallow conditions. He includes analytic solutions for both the direct and lateral transmission paths and presents a comparison of the contributions of these paths for near-surface receivers. Young (1973) presents an analysis which, while directed at deep-water applications, derived an equivalent dipole underwater source for an aircraft overflight that can be used for direct path underwater received level estimates. A detailed description of air-water sound transmission is given in *Marine Mammals and Noise* (Richardson et al., 1995a). The following is a short summary of the principal features.

Figure G-5 shows the general characteristics of sound transmission through the air-water interface. Sound from an elevated source in air is refracted upon transmission into water because of the difference in sound speeds in the two media (a ratio of about 0.23). Because of this difference, the direct sound path is totally reflected for grazing angles less than 77°, i.e., if the sound reaches the surface at an angle more than 13° from vertical. For smaller grazing angles, sound reaches an underwater observation point only by scattering from wave crests on the surface, by non-acoustic (lateral) pressure transmission from the surface, and from bottom reflections in shallow water. As a result, most of the acoustic energy transmitted into the water from a source in air arrives through a cone with a 26° apex angle extending vertically downward from the airborne source. For a moving source, the intersection of this cone with the surface traces a “footprint” directly beneath the path of the source, with the width of the footprint being a function of the altitude of the source. To a first approximation, it is only the sound transmitted within this footprint that can reach an underwater location by a direct-refracted path. Because of the large difference in the acoustic properties of water and air, the pressure field is actually doubled at the surface of the water, resulting in a 6 dB increase in pressure level at the surface. Within the direct-refracted cone, the in-air sound transmission paths are affected both by geometric spreading and by the effects of refraction.

In shallow water within the direct transmission cone, the directly transmitted sound energy is generally greater than the energy contribution from bottom reflected paths. At horizontal distances greater than the water depth, the energy transmitted by reflected paths becomes dominant, especially in shallow water. The ratio of direct to reverberant energy depends on the bottom properties. For hard bottom conditions the reverberant field persists for longer ranges than the direct field. However, with increasing horizontal distance from the airborne source, underwater sound diminishes more rapidly than does the airborne sound.

Near the surface, the laterally transmitted pressure from the airborne sound is transmitted hydrostatically underwater. Beyond the direct transmission cone this component can produce higher levels than the underwater-refracted wave. However, the lateral component is very dependent on frequency and thus on acoustic wavelength. The level received underwater is 20 dB lower than the airborne sound level at a depth equal to 0.4 wavelength.

For this application, it is necessary to have an analytical model to predict the total acoustic exposure level experienced by marine mammals near the surface and at depth near the path of an aircraft overflight. Malme and Smith (1988) described a model to calculate the acoustic energy at an underwater receiver in shallow water, including the acoustic contributions of both the direct sound field (Urick, 1972) and a depth-averaged reverberant sound field (Smith, 1974).

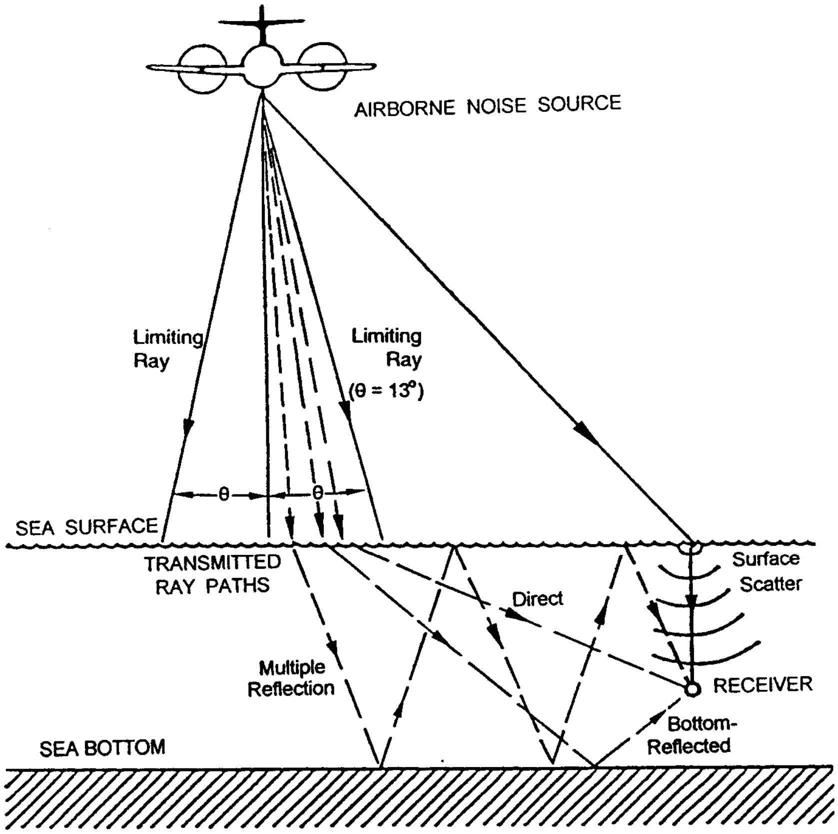


Figure G-5. Characteristics of Sound Transmission through Air-Water Interface

In the present application, the Urick (1972) analysis for the lateral wave field was also included to predict this contribution. The paths of most concern for this application are the direct-refracted path and the lateral path. These paths will likely determine the highest sound level received by mammals located nearly directly below a passing airborne source and mammals located near the surface, but at some distance away from the source track. In shallow areas near shore, bottom-reflected acoustic energy will also contribute to the total noise field, but it is likely that the direct-refracted and lateral paths will make the dominant contributions.[1]

Figure G-6 shows an example of the model prediction for a representative source-receiver geometry. The transmission loss (TL) for the direct-refracted wave, the lateral wave, and their resultant energy-addition total is shown. Directly under the aircraft, the direct-refracted wave is seen to have the lowest TL. For the shallowest receiver at a 3-ft depth, the lateral wave is seen to become dominant at about a horizontal range of 40 ft. Beyond this point the underwater level is controlled by the sound level in the air directly above the receiver and follows the same decay slope with distance. For the deeper receiver at 10 ft, the lateral wave does not become dominant until the horizontal range is about 130 ft. When sound reaches the receiver via the direct-refracted path, it decays at about 12 dB/distance doubled (dd), consistent with a surface dipole source. In

[1]The bottom-reflected reverberant sound field section of this model for offshore applications requires detailed knowledge of bottom slope and bottom composition. In view of the requirements of this application, this level of detail is not appropriate and the reflected path subroutine was not used.

contrast, when the sound reaches the receiver via the lateral path, it decays at about 6 dB/dd, consistent with the airborne monopole source. Underneath the aircraft, the drop in sound level with depth change from 3 to 10 ft is only about 2 dB, but beyond about 200 ft, a 12 dB drop occurs for the same change in depth.

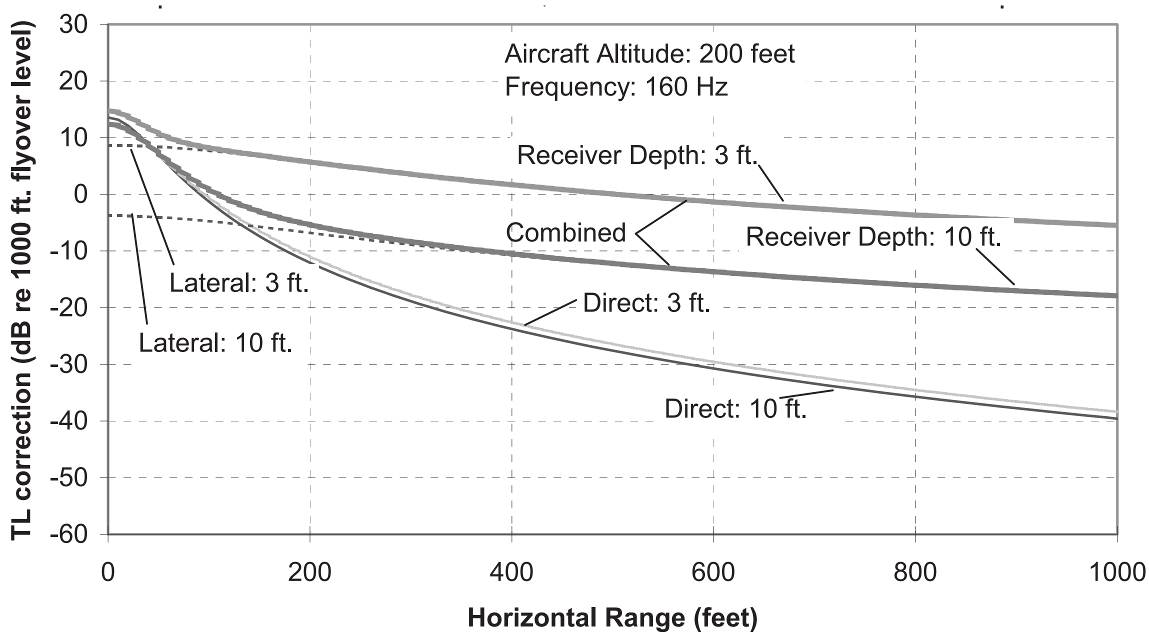


Figure G-6. Transmission Loss of Noise through Air-Water Interface, Comparison of Direct-Refracted, Lateral and Combined TL Components

Figures G-7A-C illustrate the interaction between the various parameters for different sets of variables. For clarity, only the total transmission loss curves are shown in these figures. Figure G-7A shows the influence of frequency (wavelength) change on transmission loss. Here the loss at a depth of 3 ft can be seen to increase significantly with frequency in the region where the lateral wave is dominant. Thus marine mammals near the surface will benefit from high-frequency attenuation when they are not directly below the source track. Figure G-7B shows the change in TL with receiver depth for low-frequency sound. Near the source track, a 6 dB drop in level occurs for a change in depth from 1 to 30 ft, but beyond a horizontal range of 200 ft, there is a 20 to 30 dB drop in level for the same change in receiver depth. Note, however, that for an increase in depth from 30 to 300 ft, the received level increases because of the effective source directionality. Figure G-7C shows the effect of increasing the aircraft altitude. In this case the region near the source track is affected the most with about a 38 dB drop in level for an altitude change of 50 ft to 5,000 ft. At a horizontal range of 200 ft, this drop is about 20 dB, with a decrease to 15 dB at 500 ft.

For a passing airborne source, received level at and below the surface diminishes with increasing source altitude, but the duration of exposure increases. The maximum received levels at and below the surface are inversely proportional to source altitude, but total noise energy exposure is inversely proportional to the product of source altitude and speed because of the link between altitude and duration of exposure.

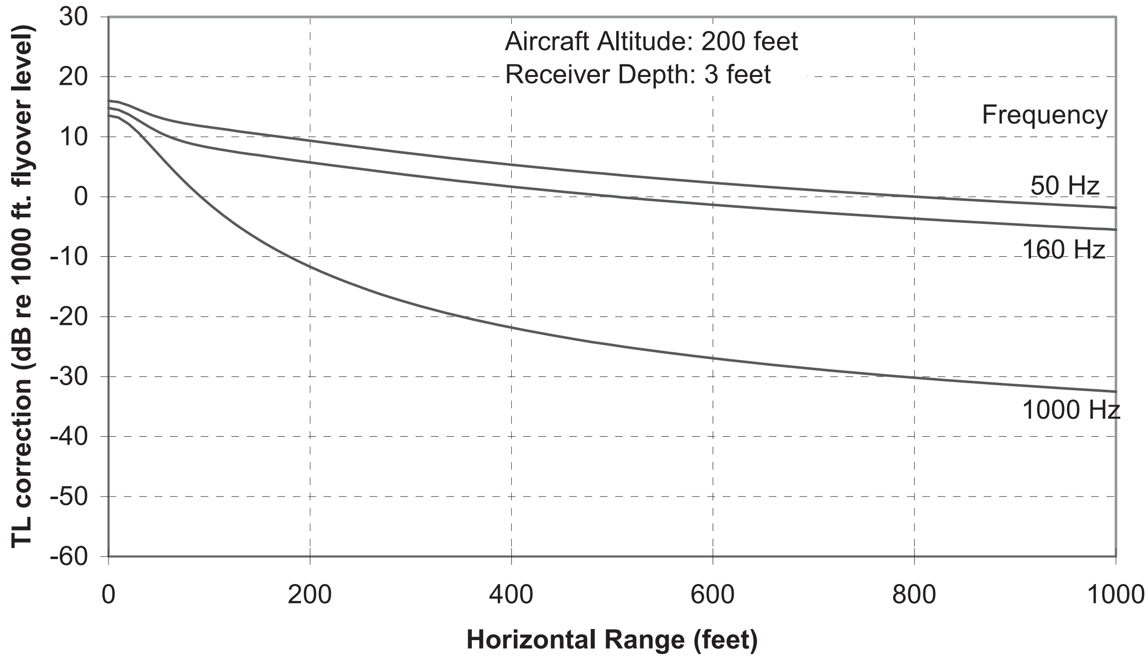


Figure G-7A. Air-Water Transmission Loss vs. Frequency

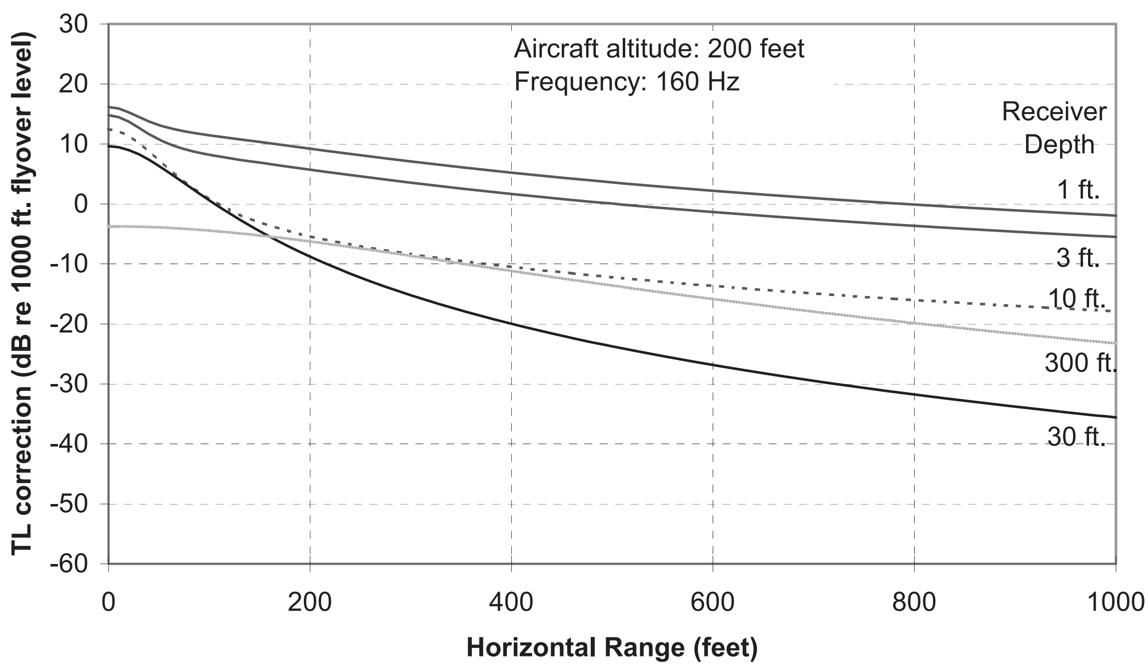


Figure G-7B. Air-Water Transmission Loss vs. Receiver Depth

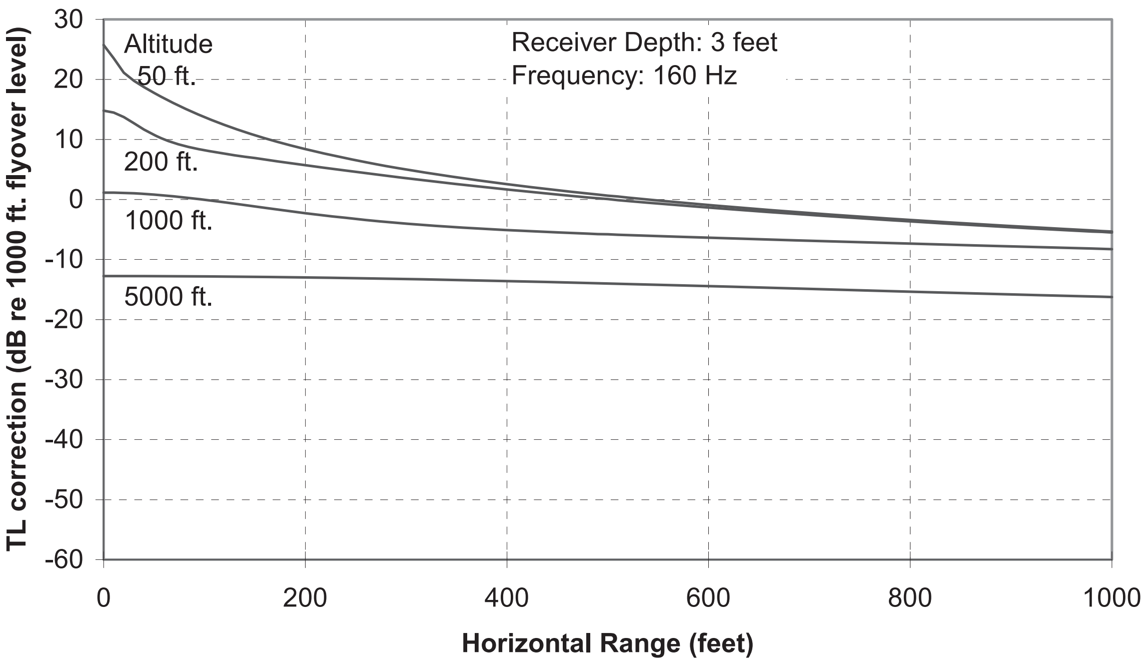


Figure G-7C. Air-Water Transmission Loss vs. Aircraft Altitude

In summary, airborne sound does not, in general, transmit well into the water because of the difference in sound speeds between air and water. If the sound reaches the surface at an angle more than 13° from vertical, the sound is generally reflected rather than transmitted into the water. While scattering from waves also facilitates sound entering the water, in the ocean this is also somewhat offset by bubbles at the surface introduced by breaking waves. A 13° cone from the source's altitude to the ocean's surface traces a "footprint" along the source's flight, but as size of the footprint increases with altitude, the sound level reaching the ocean surface decreases as a result of transmission loss through the air.

G.3.1 SUPERSONIC SOURCES

While sonic booms are not always heard at the surface, if present, a sonic boom footprint produced by a supersonic aircraft in level flight at constant speed traces a hyperbola on the sea surface. The apex of the hyperbola moves at the same speed and direction as the aircraft with the outlying arms of the hyperbola traveling at increasing oblique angles and slower speeds until the boom shock wave dissipates into a sonically propagating pressure wave at large distances from the flight path. The highest boom overpressures at the water surface are produced directly below the aircraft track. In this region the pressure-time pattern is described as an "N-wave" because of its typical shape. Aircraft size, shape, speed, and altitude determine the peak shock pressure and time duration of the N-wave. The incidence angle of the N-wave on the water surface is determined by the aircraft speed (i.e., for Mach 2 the incidence angle is 45). Thus for aircraft in level flight at speeds less than about Mach 4.3, the N-wave is totally reflected from the surface. Dives and other maneuvers at supersonic speeds of less than Mach 4.3 can generate N-waves at incidence angles that are refracted into the water, but the water source regions affected by these transient events are limited. Since the aircraft, missiles, and targets used in range activities generally operate at less than Mach 4.3, sonic boom penetration into the water from these sources occurs primarily by lateral (evanescent) propagation. Analyses by Sawyers (1968) and Cook (1969) have shown that the attenuation rate (penetration) of the boom pressure wave is related to the size, altitude and speed of the source vehicle. The attenuation of the N-wave is not related to the length of the signature in the simple way that the lateral wave penetration from subsonic sources is related to the dominant wavelength of their signature. Specific examples will be given for the supersonic vehicles used in range tests as appropriate in this EIS/OEIS.

G.4 UNDERWATER SOUND CHARACTERISTICS

Many of the general characteristics of sound and its measurement were discussed in the introduction to airborne noise characteristics. This section expands on this introduction to summarize the properties of sound underwater that are relevant to understanding the effects of range activities on the underwater marine environment in the HRC area. Since the effect of underwater sound on human habitat is not an issue (except perhaps for divers), the primary environmental concern that is addressed is the potential impact on marine mammals.

G.4.1 UNITS OF MEASUREMENT

The reference level for airborne sound is 20 μPa, consistent with the minimum level detectable by humans. For underwater sound, a reference level of 1 μPa is used because this provides a more convenient reference and because a reference based on the threshold of human hearing in air is irrelevant. For this reason, as well as the different propagation properties of air and water, it is not meaningful to compare the levels of sound received in air (measured in dB re 20 μPa) and in water (in dB re 1 μPa) without adding the 26 dB correction factor to the airborne sound levels.

G.4.2 SOURCE CHARACTERISTICS

The most significant range-related sources of underwater sound operating on the HRC are the ships used in Anti-Submarine Warfare Exercises. Because of their slow speed compared to most of the airborne sources considered in the last section, they can be considered to be continuous sound sources. The primary underwater transient sound sources are naval gunfire, aircraft delivered bombs and gunfire, missile launches, and water surface impacts from missiles and falling debris. All sources are subsonic or stationary in water. While supersonic underwater shock waves are produced at short ranges by underwater explosions, no sources operate at supersonic speeds in water.

G.4.3 UNDERWATER SOUND TRANSMISSION

Airborne sources transmit most of their acoustic energy to the surface by direct paths which attenuate sound energy by spherical divergence (spreading) and molecular absorption. For sound propagating along oblique paths relative to the ground plane, there may also be attenuation (or amplification) by refraction (bending) from sound speed gradients caused by wind and temperature changes with altitude. There may also be multipath transmission caused by convergence of several refracted and reflected sound rays, but this is generally not important for air-to-ground transmission. However, for underwater sound, refracted and multipath transmission is often more important than direct path transmission, particularly for high-power sound sources capable of transmitting sound energy to large distances.

A surface layer sound channel often enhances sound transmission from a surface ship to a shallow receiver in tropical and mid-latitude deep-water areas. This channel is produced when a mixed isothermal surface layer is developed by wave action. An upward refracting sound gradient, produced by the pressure difference within the layer, traps a significant amount of the sound energy within the layer (Sound travels faster with increasing depth.) This results in cylindrical rather than spherical spreading. This effect is particularly observable at high frequencies where the sound wavelengths are short compared to the layer depth. When the mixed layer is thin or not well defined, the underlying thermocline may extend toward the surface, resulting in downward refraction at all frequencies and a significant increase in transmission loss at shorter ranges where bottom reflected sound energy is normally less than the directly transmitted sound component.

In shallow water areas sound is trapped by reflection between the surface and bottom interfaces. This often results in higher transmission loss than in deep water because of the loss that occurs with each reflection, especially from soft or rough bottom material. However, in areas with a highly reflective bottom, the transmission loss may be less than in deep water areas since cylindrical spreading may occur.

The many interacting variables involved in prediction of underwater transmission loss have led to the development of analytical and computer models. One or more of these models will be used in analyzing the potential impact of the underwater sound sources in the range areas.

G.4.4 UNDERWATER AMBIENT SOUND

For Hawaii, Au et al., (2000) have demonstrated that ambient sound pressure levels during the peak of humpback whale “season” (specifically between mid-February and mid-March) are approximately 120 dB re µ1 Pa with spectral peaks at 315 Hz and 630 Hz. For the ocean in general, above 500 Hz, deep ocean ambient sound is produced primarily by wind and sea state conditions. Below 500 Hz, the ambient sound levels are strongly related to ship traffic, both near and far. In shallow water near continents and islands, surf is also a significant factor. Wenz (1962) and Urick (1983) are among many contributors to the literature on underwater ambient sound. Figure G-8, based on these two sources, was adapted by Malme et al. (1989) to show ambient sound spectra in 1/3-octave bands for a range of sea state and ship traffic conditions.

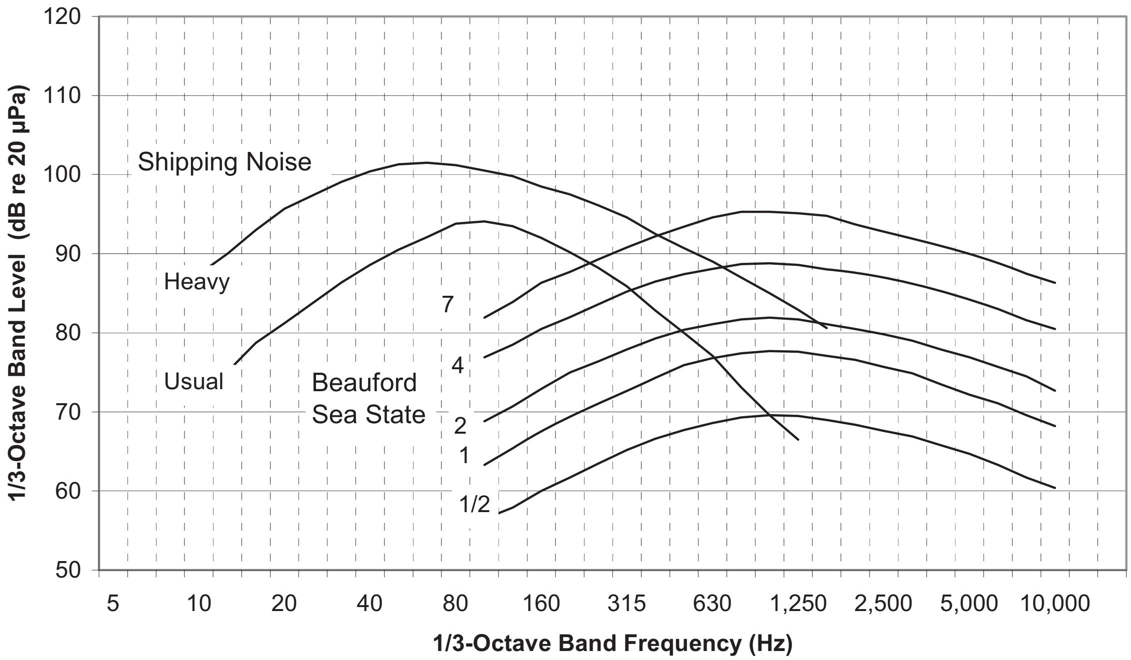


Figure G-8. Underwater Ambient Sound

Wind

On a 1/3-octave basis, wind-related ambient sound in shallow water tends to peak at about 1 kHz (see Figure G-8). Levels in 1/3-octave bands generally decrease at a rate of 3 to 4 dB per octave at progressively higher frequencies and at about 6 dB per octave at progressively lower frequencies. Sound levels increase at a rate of 5 to 6 dB per doubling of wind speed. At a frequency of about 1 kHz, maximum 1/3-octave band levels are frequently observed at 95 dB referenced to 1 μPa for sustained winds of 34 to 40 knots and at about 82 dB for winds in the 7 to 10 knot range. Wave action and spray are the primary causes of wind-related ambient sound; consequently, the wind-related noise component is strongly dependent on wind duration and fetch as well as water depth, bottom topography, and proximity to topographic features such as islands and shore. A sea state scale, which is related to sea surface conditions as a function of wind conditions, is commonly used in categorizing wind-related ambient sound. The curves for wind-related ambient sound shown in Figure G-8 are reasonable averages, although relatively large departures from these curves can be experienced depending on site location and other factors such as bottom topography and proximity to island or land features.

Surf

Very few data have been published relating specifically to local sound levels due to surf in offshore areas along mainland and island coasts. Wilson et al. (1985) present underwater sound levels for wind-driven surf along the exposed Monterey Bay coast, as measured at a variety of distances from the surf zone. Wind conditions varied from 25 to 35 knots. They vary from 110 to 120 dB in the 100 to 1,000 Hz band at a distance of 650 ft from the surf zone, down to levels of 96 to 103 dB in the same band 4.6 nm from the surf zone. Assuming that these levels are also representative near shorelines in the HRC area, surf sound in the 100 to 500 Hz band will be 15 to 30 dB above that due to wind-related noise in the open ocean under similar wind speed conditions.

Distant Shipping

The presence of a relatively constant low-frequency component in ambient sound within the 10 to 200 Hz band has been observed for many years and has been related to distant ship traffic as summarized by Wenz (1962) and Urick (1983). Low-frequency energy radiated primarily by cavitating propellers and by engine excitation of the ship hull is propagated efficiently in the deep ocean to distances of 100 nm or more. Higher frequencies do not propagate well to these distances due to acoustic absorption. Also, high-frequency sounds radiated by relatively nearby vessels will frequently be masked by local wind-related sound. Thus, distant shipping contributes little or no sound at high frequency. Distant ship-generated low-frequency sound incurs more attenuation when it propagates across continental shelf regions and into shallow offshore areas than occurs in the deep ocean.

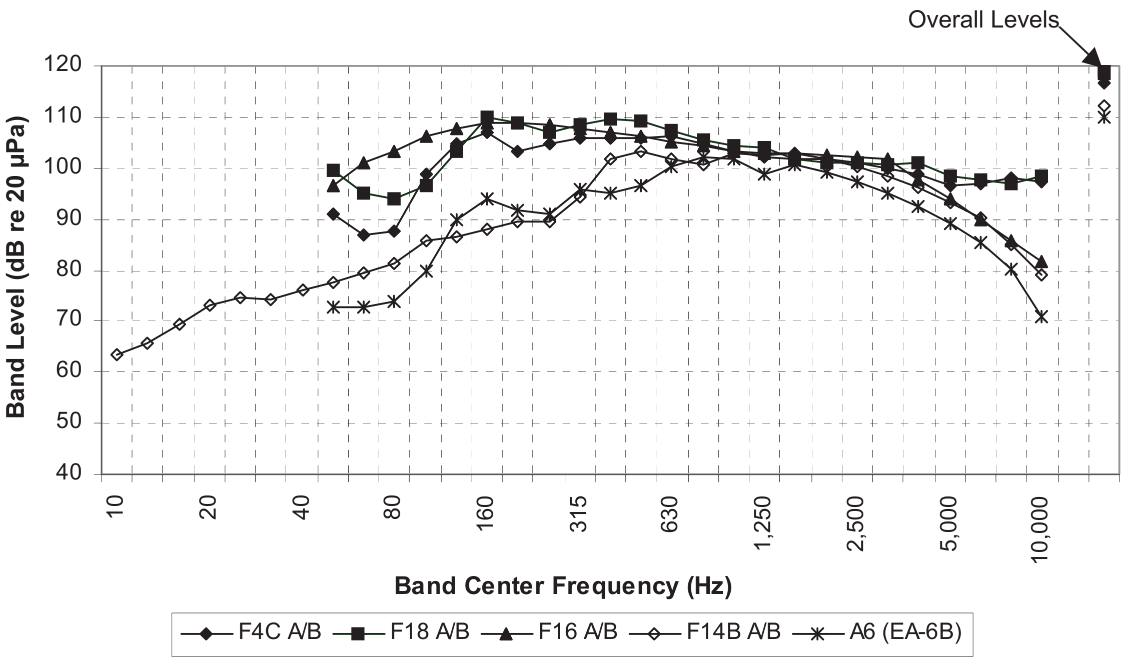
Figure G-8 also provides two curves that approximate the upper bounds of distant ship traffic sound. The upper curve represents the sound level at sites exposed to heavily used shipping lanes. The lower curve represents moderate or distant shipping sound as measured in shallow water. As shown, highest observed ambient sound levels for these two categories are 102 dB and 94 dB, respectively, in the 60 to 100 Hz frequency range. In shallow water the received sound level from distant ship traffic can be as much as 10 dB below the lower curve given in Figure G-8, depending on site location on the continental shelf. In fact, some offshore areas can be effectively shielded from this low-frequency component of shipping sound due to sound propagation loss effects.

Note that the shipping sound level curves shown in Figure G-8 show typical received levels attributable to *distant* shipping. Considerably higher levels can be received when a ship is present within a few miles.

G.4.5 MARINE MAMMAL SOUND METRICS

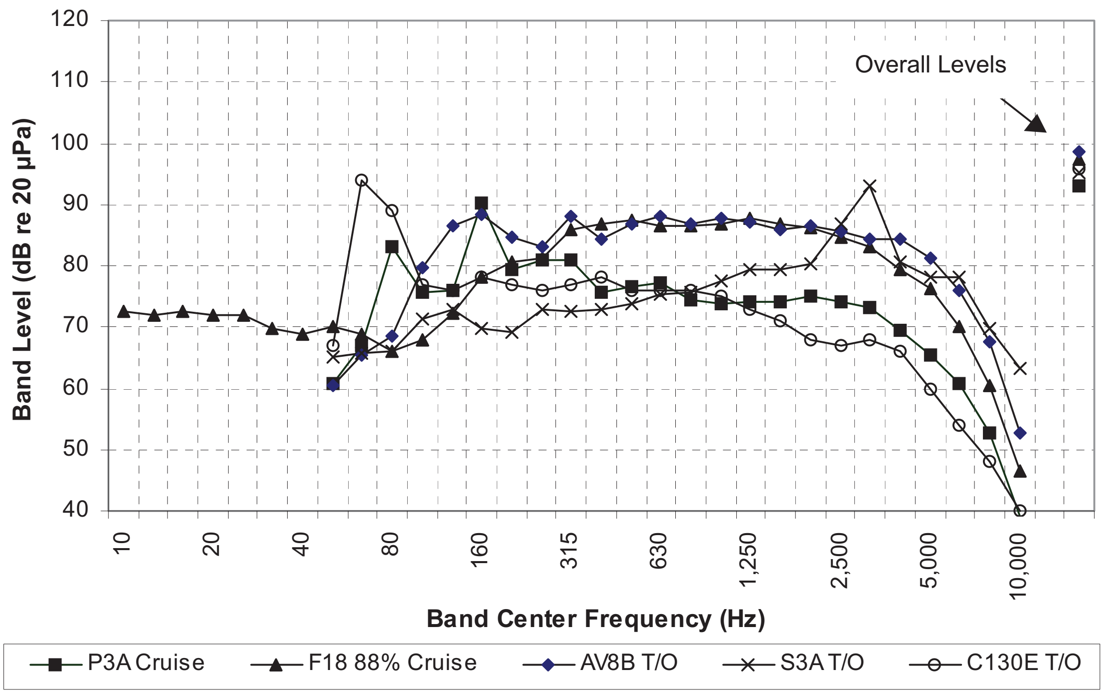
Sound received at and below the sea surface is relevant to marine mammals and some other marine animals at sea. The spectral composition and overall level of each airborne noise source must both be considered in assessing potential impacts on marine mammals present at sea in the HRC. As described earlier, the most significant sources are low-flying aircraft and their related weapons, naval gunfire, targets, missiles, and debris impacts. Brief sound transients or impulses from surface missile launches, low level explosions, and gunfire may also be important during training.

Aircraft spectrum information was obtained from the U.S. Air Force Armstrong Laboratory for various aircraft types (Air Force Aerospace Medical Research Laboratory, 1990). Data for some additional types of aircraft occasionally used on the HRC were also included. The information obtained is summarized in the 1/3-octave band spectra shown in Figure G-9A (for fighter and attack aircraft), Figure G-9B (selected HRC aircraft), and Figure G-9C (helicopters). Most of these spectra represent received levels near the surface during overflights at 1,000 ft above sea level under standard atmospheric conditions (59° F, 70 percent relative humidity). The data shown in this standard format can be adjusted for different aircraft altitudes and other atmospheric attenuation conditions—an important consideration at high frequencies.



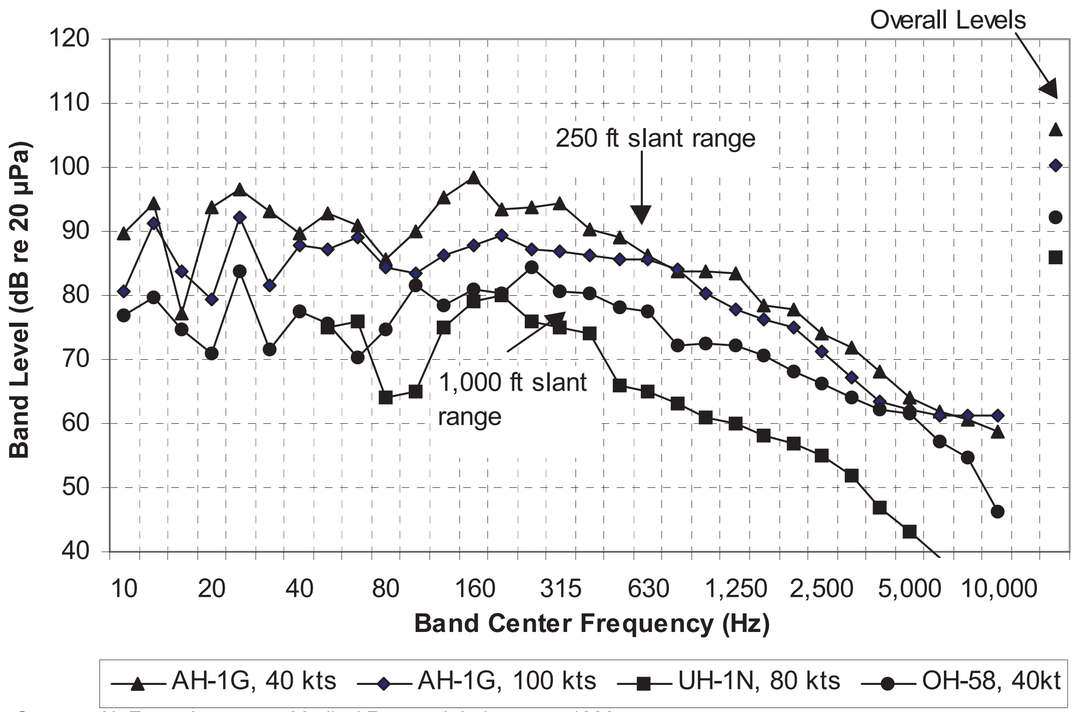
Source: Air Force Aerospace Medical Research Laboratory, 1990.

Figure G-9A. Noise Spectra: Fighter and Attack Aircraft



T/O = takeoff
Source: Air Force Aerospace Medical Research Laboratory, 1990.

Figure G-9B. Noise Spectra: Selected HRC Aircraft



Source: Air Force Aerospace Medical Research Laboratory, 1990.

Figure G-9C. Noise Spectra: Helicopters

The aircraft spectra can be compared to the shapes and quantitative features of marine mammal audiograms, when known, to determine the weighting functions and overall level adjustments needed to estimate the perceived overall levels produced during close encounters. These levels can then be compared to known or assumed impact thresholds to determine whether a detailed analysis is needed. If a detailed analysis is indicated, then contour plots can be calculated to estimate the total number of animals potentially affected by an encounter scenario.

G.4.6 SONIC BOOM PROPAGATION INTO THE WATER

Aircraft Overflights

Supersonic activities in the HRC result in sonic boom penetration of the water in the operating area. Boom signatures were estimated using the Air Force's PCBOOM3 model to determine the potential for sound impacts near or at the surface. The F-4 fighter was used in this analysis since it is representative of aircraft using the range. Table G-4 shows the underwater boom parameters at locations near the water surface together with the estimated attenuation rate of peak pressure with depth using a method developed by Sawyers (1968).

Table G-4. Underwater Sonic Boom Parameters for F-4 Overflight

Sonic Boom Parameters			Depth Peak Pressure Loss (feet)					
Speed	Alt. (feet)	T (msec)	Lp (1μPa)	CSEL	ASEL	6 dB	10 dB	20 dB
M1.2	10,000	103	168.0	143.9	129.6	11.5	24.6	68.9
M1.2	5,000	88	179.9	148.8	134.3	9.8	21.3	59.7
M1.2	1,000	64	182.9	159.1	145.6	6.9	15.1	42.6
M2.2	1,000	44	186.7	163.1	149.7	9.7	21.0	58.4

Source: Ogden Environmental, 1997.

Missile and Target Overflights

Low-level supersonic target and missile flights also produce significant sounds underwater from sonic booms. Specific data are not available for the Vandal target under normal flight conditions at low altitudes of 100 ft down to 20 ft. The required sonic boom estimates were made using a method developed by Carlson (1978) and adapted for model-based analysis by Lee and Downing (1996). This analysis assumes that the essential boom signature is a simple “N-wave” as is typically measured for supersonic aircraft passing at high altitudes (hundreds of feet). At lower altitude overflights, which are of interest here, the pressure contributions from the shape variations on the aircraft body and wings become observable, and at very low altitudes the signature is no longer a simple N-wave.

The acoustic impact analysis requires estimates of both the peak pressure level produced by a Vandal boom and the total sound energy exposure. The peak pressure level produced at close range (near field) can be influenced by contributions from minor peaks in the waveform. A relevant study by McLean and Shrout (1966) made a comparison of near-field boom waveforms calculated with appropriate near-field theory with waveforms predicted by far-field theory for representative aircraft. The results showed that the peaks predicted by the near-field theory were generally about 10 percent lower than those predicted at the same range by far-field theory. Thus in this application, the use of the Carlson method would be expected to yield conservative results.

The energy density spectrum and total sound energy exposure were estimated using Fourier analysis of the predicted N-wave to obtain the unweighted (flat) energy density spectrum and the F-SEL. This spectrum was then A-weighted to estimate the A-SEL. The A-SEL is about 9 dB below the F-SEL. On the issue of near-field effects, the change in frequency distribution of the pressure signature with distance must be considered. The near-field signature has more of its energy in smaller shock waves associated with the details of the airframe (e.g., fins, fuselage changes in area, etc.). The peaks associated with the far-field N signature have not yet fully developed so more of the acoustic energy appears at higher frequencies. A coalescing process is caused by non-linear propagation of high-pressure sound in the atmosphere (sound travels faster at higher pressures) that occurs with distance as the sound wave propagates outward from the flight path. Initially smooth high-pressure fluctuations compress into shock waves. Thus, because of the increased high-frequency content, the resulting total energy of a near-field signature measured at 20 ft would likely be reduced less by the A-weighting process than would the total energy of an N-wave approximation. However, this difference is not be expected to be more than 2 to 3 dB because of the large shifts in spectrum energy that would be required during propagation.

An analytic model was developed to predict the boom signature produced by Vandal flights that used the Vandal dimensions and assumed a level flight at Mach 2.1 at various altitudes. For an altitude of 20 ft, the predicted overpressure underwater at the surface is 300 pounds per square foot or 203 dB re 1 μPa with a boom duration of 4.8 milliseconds. The peak level is estimated to be 10 dB lower at a depth of 1.5 ft and 20 dB lower at a depth of 5 ft, based on an analysis developed by Sawyers (1968).