ACOUSTIC MEASUREMENTS IN COOK INLET, ALASKA, DURING AUGUST 2001

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1.0 Executive Summary

During August 2001 Greeneridge Sciences, Inc., made underwater and in-air recordings of various sound sources in Cook Inlet, AK. The objective was to quantify the acoustic environment that beluga whales may be subjected to in the Inlet. Sounds were analyzed with respect to their broadband and one-third octave band levels, and their spectral composition. Repeated measurements of the same source at different distances provided information on transmission loss. Four main types of sound sources were analyzed: (1) overflights by commercial and military aircraft departing or landing at Anchorage International Airport and Elmendorf Air Force Base, respectively; (2) the *Phillips A* oil platform located in the northwestern part of Cook Inlet; (3) large and small vessels in Anchorage harbor; and (4) ambient sounds in areas removed from industrial activities.

Recordings were made during aircraft overflights seaward of Anchorage International Airport (ANC), where commercial jets and airplanes were taking off, and Elmendorf Air Force Base (AFB), where military jets (mainly F-15s) were landing. Peak underwater broadband levels during overflights reached 125 dB re 1 μPa at ANC and 135 dB re 1 μPa at the AFB. "Ambient" broadband levels, recorded in the same locations while no overflights were taking place, were higher for the AFB (119 dB re 1 μPa) than for ANC (105 dB re 1 μPa). A-weighted in-air broadband levels reached 95 dBA re 20 μPa for both airports. Spectral composition for both commercial and military jets was broadband in nature with most of the energy below 2 kHz.

Recordings were made at 6 stations located 0.3 to 19 km from the *Phillips A* oil platform. Underwater broadband levels were highest 1.2 km from the platform (119 dB re 1 μPa) and decreased with distance, reaching background levels by the farthest station (19 km). Several tones at frequencies of 60 to 105 Hz likely originated at the platform and had spreading loss terms of -16 to -24 dB per tenfold change in distance. A-weighted broadband levels in air reached 65 dBA re 20 μPa 0.3 km from the platform and decreased at a rate of -16 dB per tenfold change in distance.

Both large ships (i.e. cargo-bulk carrier *Emerald Bulker*) and small craft (i.e., Avon rubber boat) were recorded in Anchorage harbor. The highest underwater broadband levels were obtained while a tug was docking a gravel barge and reached 149 dB re 1 μPa at a distance of 100 m. Spreading loss terms for most of the underwater recordings in the harbor area were between -14 and -21 dB re 1 μPa. Beluga whales were observed in the harbor area close to a cargo-freight ship during one of the recordings, when broadband levels would have been close to 125 dB re 1 μPa. Ship noise was mainly low-frequency in nature, with most of the energy below 1 kHz.

Six locations removed from industrial activities were sampled for ambient sound levels. The lowest broadband underwater levels were obtained at Birchwood, a location up the Knik Arm which is frequented by beluga whales, and averaged 95 dB re 1 μPa. The highest underwater broadband levels were obtained north of Point Possession during the incoming tide and reached 124 dB re 1 μPa. These ambient sound levels are comparable to those recorded in the Beaufort Sea away from industrial activities. When compared to the Birchwood recording, an ambient recording from Anchorage harbor showed a reasonably even increase in sound pressure levels of 20-40 dB across all frequencies sampled (4 to 20,000 Hz). In contrast, the highest SPLs in the recording made north of Point Possession were between 1 and 10 kHz and were attributed to tide noises.

The table below summarizes the broadband values presented in the report.

TABLE 1. Summary of mean and / or peak broadband levels presented in this report for various sources. Bandwidth is 10 - 20,000 Hz for all underwater data (U) and 20 - 18,000 Hz for all in-air data (A). The units are dB re 1 µPa for all underwater data and dBA re 20 µPa for all in-air data.

Source	Underwater	In-air	Comments
Birchwood, ambient	95 dB	N.A.	Mean value, quietest recording
Mouth of Little Susitna River, ambient	100 dB	N.A.	Mean value
Anchorage airport (ANC), ambient	105 dB	48 dBA	Mean values
Between Fire Is. and Little Susitna River	113 dB	N.A.	Mean value
Anchorage harbor, ambient	113 dB	N.A.	Mean value
Eagle River, ambient	118 dB	N.A.	Mean value
Elmendorf AFB, ambient	119 dB	68 dBA	Mean values
North of Point Possession, ambient	120 dB	N.A.	Mean value
Overflights, commercial aircraft taking off from ANC	110 - 124 dB	72 - 95 dBA	Range of values for 8 (U) and 10 (A) different aircraft
Overflights, military jets (mainly F-15s) landing at Elmendorf AFB	122 - 134 dB	79 - 94 dBA	Range of values for 2 (U) and 9 (A) military jets
Phillips A oil platform	119 dB 97 - 111 dB	65 dBA 30 - 64 dBA	Highest value recorded Range of means at distances of 0.3 to 19 km from platform
Tug *Leo* docking gravel barge *Katie II*	149 dB	N.A.	Highest value, recorded at 102 m
Avon rubber boat driving by at full speed	142 dB	N.A.	Highest value, recorded at 8.5 m
Emerald Bulker (cargo-bulk carrier) departing	134 dB	N.A.	Highest value, recorded at 540 m
Northern Lights (cargo-freight ship), docked	126 dB	63 dBA	Highest value, recorded at 114 m (U) and 85 m (A)

Beluga whales are able to hear an unusually wide range of frequencies, covering most natural and man-made sounds. Where their hearing is keenest (10 - 100 kHz) is above the frequency range of most industrial noise, and at low frequencies (<100 Hz) beluga hearing threshold levels may be comparable to or exceed one-third octave band levels for industrial activities reported on in this study. None of the SPLs recorded approached values that might be expected to injure belugas, but for certain frequencies in some recordings, one-third octave band levels were as much as 50 dB higher than the whales' hearing threshold. There is extreme variability in beluga responses to anthropogenic sound, but in industrialized areas the whales seem to have habituated to sounds from ships and industry.

2.0 Introduction

2.1 Background

A small, genetically and geographically isolated population of beluga whales (*Delphinapterus leucas,* Pallas 1776), inhabits the semi-enclosed waters of Cook Inlet, Alaska (Rugh *et al.* 2000, O'Corry-Crowe *et al.* 1997, see Figure 1). After abundance estimates showed a 50% population decline between 1994 and 1998 (Hobbs *et al.* 2000), the National Marine Fisheries Service (NMFS) designated the stock as depleted under the Marine Mammal Protection Act (MMPA) on May 31, 2000 (65 FR 59834). In October 2000 NMFS drafted an EIS on Federal actions associated with management and recovery of these belugas. An important part of this EIS was to identify factors that may have led to the decline and to implement measures to control these factors (NMFS, 2000a).

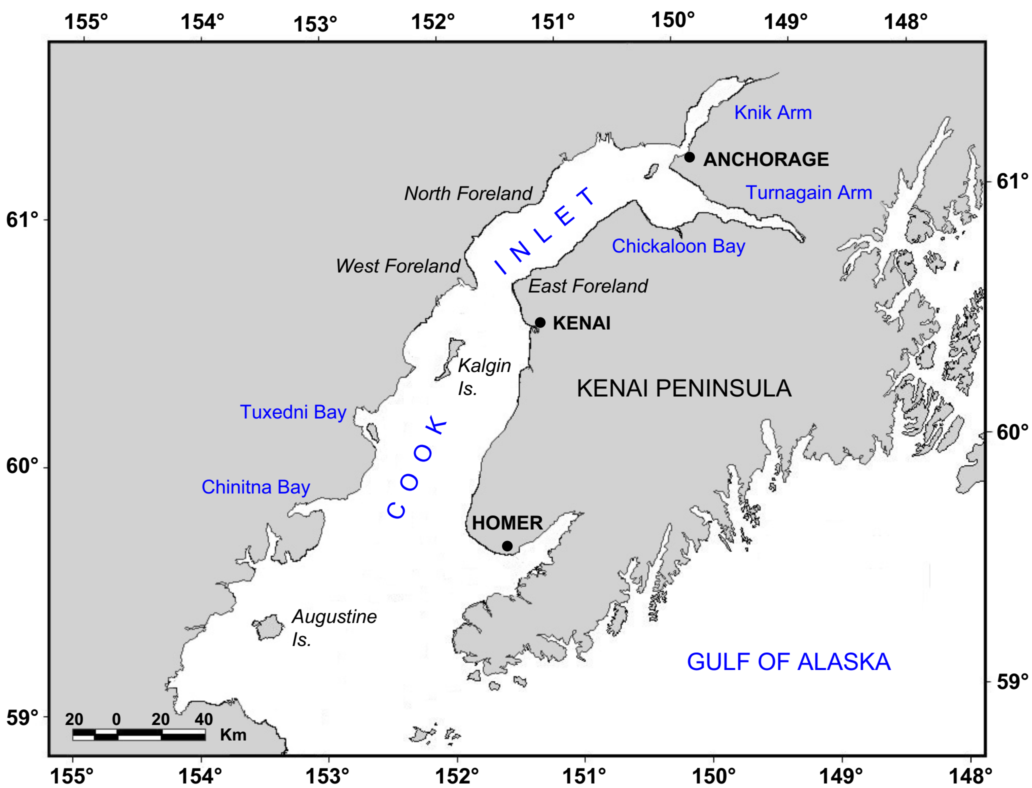

FIGURE 1: Map of the Cook Inlet area on the southern coast of Alaska.

Cook Inlet is a large, semi-enclosed tidal estuary on the southern coast of Alaska, between the latitudes of about 59 and 61.5 degrees north. It is approximately 370 km (230 miles) long, 48 km (30 miles) wide and is rather shallow (generally no more than 60 m = 200 feet). The area's main urban center is Anchorage, located close to the Inlet's northern end. The Inlet receives the waters from many large rivers, particularly at its northern end, while the southern end has marine connections with Shelikof Strait and the Gulf of Alaska. This situation creates gradations in turbidity, salinity and temperature both in time (i.e., decreased freshwater input in the winter) and space. The bottom substrate in the Inlet is a mixture of cobbles, pebbles, silt and clay (Moore *et al.* 2000); the major rivers that empty into the Inlet contribute huge amounts of glacial sediments. Finally, Cook Inlet has one of the largest tides of the American continent, with a mean diurnal range in Anchorage of about 9.5 m (30 feet). This enormous tidal range is the main driving force of surface circulation, with current velocities of on average about 3 knots but locally as high as 12 knots (Moore *et al.* 2000). It is also the most important natural factor to take into account when measuring underwater sound levels, as tidal noises can be important contributors to ambient levels (Urick 1983).

The Cook Inlet region is a major population center in the State of Alaska. The industrial development that has taken place in the area over the last couple of decades has increased ambient sound levels, both underwater and in air, from ship traffic, construction activities, oil development and recreational activities. Concern has been expressed over whether these increased sound levels could have contributed to the decline of the Cook Inlet beluga whale population or whether these sounds will adversely affect their recovery.

2.2 Objective

The objective of this work is to quantify the acoustic environment that beluga whales may be subjected to in Cook Inlet. Underwater and in-air recordings were made in locations both adjacent to industrial activities and away from man-made sounds. The recordings were analyzed to document both broadband and one-third octave band sound pressure levels and spectral characteristics. Recordings of the same sound at different distances provided information on transmission loss, both in-air and underwater.

2.3 Beluga whale hearing sensitivity

Since this report investigates industrial and non-industrial sound levels and frequency characteristics as they relate to beluga whales, it seems appropriate to briefly summarize the range and sensitivity of beluga hearing underwater. Their peak sensitivity is between 10 and 100 kHz (summarized in Richardson *et al.* 1995b); at the most sensitive frequencies within that range their hearing threshold[1] approaches 42 dB re 1 μPa. Above 100 kHz their sensitivity drops off very fast but the bandwidth of their hearing extends to as high as 150 kHz (Au 1993); below 8 kHz the decrease in sensitivity is more gradual, approximately 11 dB per octave (Awbrey *et al.* 1988). Beluga whales are able to hear frequencies as low as 40-75 Hz (Johnson *et al.* 1989), but at these frequencies their sensitivity is quite poor (the threshold level[1] at 40 Hz is on the order of 140 dB re 1 μPa). For comparison, humans with the keenest hearing have a bandwidth about one-eight that of beluga whales (Au 1993). This type of information is obtained from behavioral audiograms on trained captive animals. Audiograms represent the lowest levels of sound that an animal can detect in a quiet environment, which is usually different from the situation animals are subjected to in the wild. Critical ratios express the amount (in dB) by which a pure tone signal must exceed the spectrum level background noise (in dB re 1 μPa^2/Hz) in order to be audible. In beluga whales, critical ratios are on average below 20 dB (re 1 Hz)

1. Level at which the sound is just barely detectable by the animal.

up to frequencies of about 3 kHz; at higher frequencies the critical ratios continue increasing exponentially, reaching 25-30 dB at 20 kHz and 40-50 dB at 100 kHz (Johnson *et al.* 1989). Finally, a recent paper showed that depth (i.e., pressure) has no effect on beluga whales' hearing sensitivity (Ridgway *et al.* 2001). The same study also found that threshold levels for 500 Hz were 16-21 dB lower than previously-published numbers (i.e., Awbrey *et al.* 1988, Johnson *et al.* 1989) and hypothesized that this difference may be attributable to differences in methodology (Schusterman 1974).

3.0 Methods

Underwater (U) and in-air (A) recordings were made in Cook Inlet on August 21-24 2001 (see Figure 2) and included the following sources:

1. commercial jets and airplanes departing from Anchorage International Airport and military jets landing at Elmendorf Air Force Base (U, A);
2. the *Phillips A* oil platform located west southwest of Anchorage (U, A);
3. large and small vessels in Anchorage harbor, including the docked cargo-freight ship *Northern Lights* (U, A), the cargo-bulk carrier *Emerald Bulker* being maneuvered by two tugs (U) and then departing (U), the gravel barge *Katie II* being maneuvered by the tug *Leo* (U), a Boston Whaler (U) and an Avon rubber boat (U); and
4. ambient sounds in areas removed from industrial activities and known to be frequented by beluga whales, including the mouth of the Little Susitna River (U), a location between Little Susitna River and Fire Island (U), Birchwood (U), the mouth of Eagle River (U) and a location north of Point Possession (U, A).

3.1 Equipment

The sensors consisted of a hydrophone and a microphone, both calibrated. The hydrophone was an International Transducer Corporation (ITC) model 6050C, which includes a low-noise preamplifier at the sensor and a 98 ft. (30 m) cable. The hydrophone cable was attached with cable ties to a fairing to eliminate strumming problems. Hydrophone signals were amplified with an adjustable-gain postamplifier. The omnidirectional microphone was a G.R.A.S. Sound and Vibration 1/2" prepolarized free-field microphone model 40AE with an ICP preamplifier model TMS426C01 and a windscreen. Microphone signals were amplified with an adjustable-gain postamplifier.

Hydrophone and microphone signals were recorded at a sampling rate of 48 kHz on two channels of a SONY model PC208Ax instrumentation-quality digital audio tape (DAT) recorder. Recorded signals were transformed into calibrated signals that were nearly flat with frequency from 4 to 20,000 Hz for the hydrophone and from 20 to 18,000 Hz for the microphone. Quantization was 16 bits, providing a dynamic range of >80 dB between an overloaded signal and the quantization noise. A memo channel on the tape recorder was used for voice announcements, and the date and time were recorded automatically.

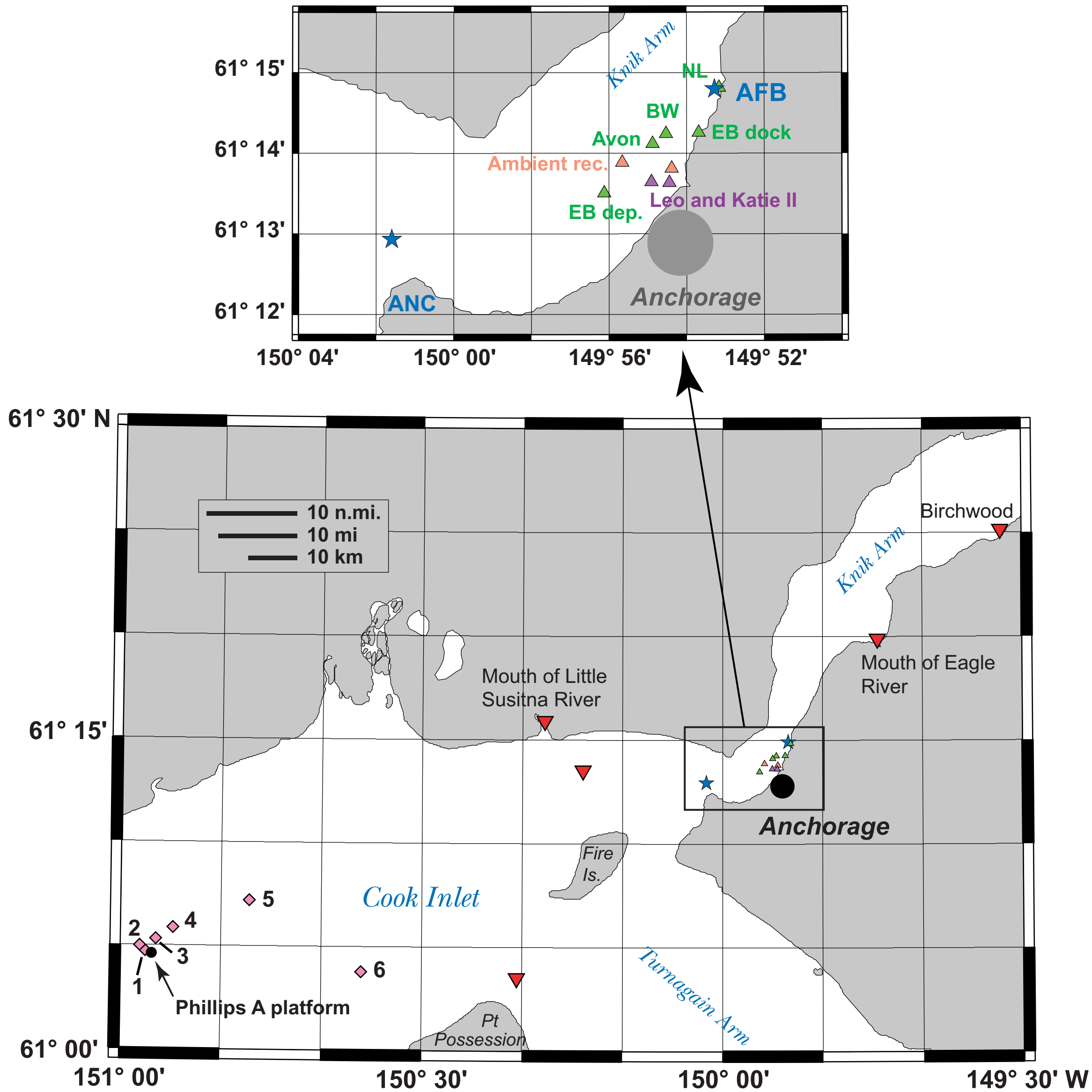

FIGURE 2: Map of Cook Inlet, Alaska, showing the recording locations during 21-24 August 2001. Locations marked are those of overflight recordings seaward of Anchorage International Airport (ANC) and Elmendorf Air Force Base (AFB) (blue stars, see section 4.1); recording stations 1-6 for measurement of the *Phillips A* platform (pink diamonds, see section 4.2); vessels in Anchorage harbor (purple, green and orange triangles, see section 4.3); and ambient sound level recordings (red inverted triangles, see section 4.4). **NL** = *Northern Lights*, **EB** = *Emerald Bulker*, **BW** = Boston Whaler

3.2 Field Procedures

Recordings were made from an Avon rubber craft belonging to NMFS in Anchorage. For the sound measurements of the *Phillips A* platform in the western part of Cook Inlet the M/V *Stellar Wind* was used as a recording platform.

After selecting an appropriate recording location, the hydrophone (to which was attached a 5-lb. weight) was lowered into the water. The hydrophone was connected to a spar buoy for the measurements of the *Phillips A* platform to isolate it from waves and boat motion; as it turned out this was not necessary since sea state conditions were ideal (see section 4.2.1). Hydrophone depth was 10 m, unless the water was too shallow, in which case the hydrophone was placed at 6 m (this was the case for the recordings at the mouth of Little Susitna River, at Birchwood and for the tug and barge recording in Anchorage harbor). A depth reading was taken with the recording vessel's depth sounder before all sound-generating devices (engine, generator, depth sounder) on that vessel were turned off. When used, the microphone was positioned in such a way that it had an unobstructed path to the targeted sound source at all times. On the Avon rubber boat the microphone was attached to an antenna about 2 m above water level. On the *Stellar Wind* it was held at arm's length about 1.5 m above the deck of the vessel by one of the field crew.

During recording, the vessel drifted with the current. Recording location coordinates were obtained with a hand-held GPS receiver (Garmin model 12XL), usually at the beginning and at the end of each recording, but always at least once. Distances to nearby (<800 m) sound sources were measured with a laser rangefinder (Bushnell model # 20-0880); readings were taken regularly and were used to calculate the recording vessel's drift rate in relation to the sound source. Drift rate and direction as calculated by the GPS receiver were also recorded. During overflights the aircraft's elevation angle (in relation to the horizon, i.e., straight overhead = 90°) was estimated by three members of the field crew and the average was used. Wind speed and sea state records were kept throughout the recordings.

To measure the sound pressure levels produced by small vessels, recordings were made while a Boston Whaler and an Avon rubber boat drove by the recording vessel at full speed. During the passes, distance readings were taken as often as possible with the laser rangefinder and were recorded directly onto the voice channel of the tape recorder.

A total of 157 minutes of underwater recordings and 93 minutes of in-air recordings were obtained.

3.3 Signal Analysis

The recorded, digitized hydrophone and microphone signals were transferred directly to a computer hard drive as time series. They were then equalized and calibrated in units of sound pressure with flat frequency response over the data bandwidth (4 - 20,000 Hz). Analysis was done using MATLAB (The MathWorks, 3 Apple Hill Drive, Natick, MA 01760-2098) routines and custom programs. For each recording, a sound pressure time series (waveform) was plotted; three examples are shown in Figure 3. In general, these plots showed varying levels as sound sources approached or receded, or started and stopped. The sound was played via a speaker to help the analyst match notes from the field with the recorded sounds. The sound waveform was used to select representative samples for further analysis. If the overall sound pressure level (SPL) varied little with time, at least two 8.5-s samples were selected from the recording and analyzed. If the sound waveform showed fluctuations in the SPL (as in Fig. 3***A***), then samples were taken from both the stronger and the weaker sections of the recording.

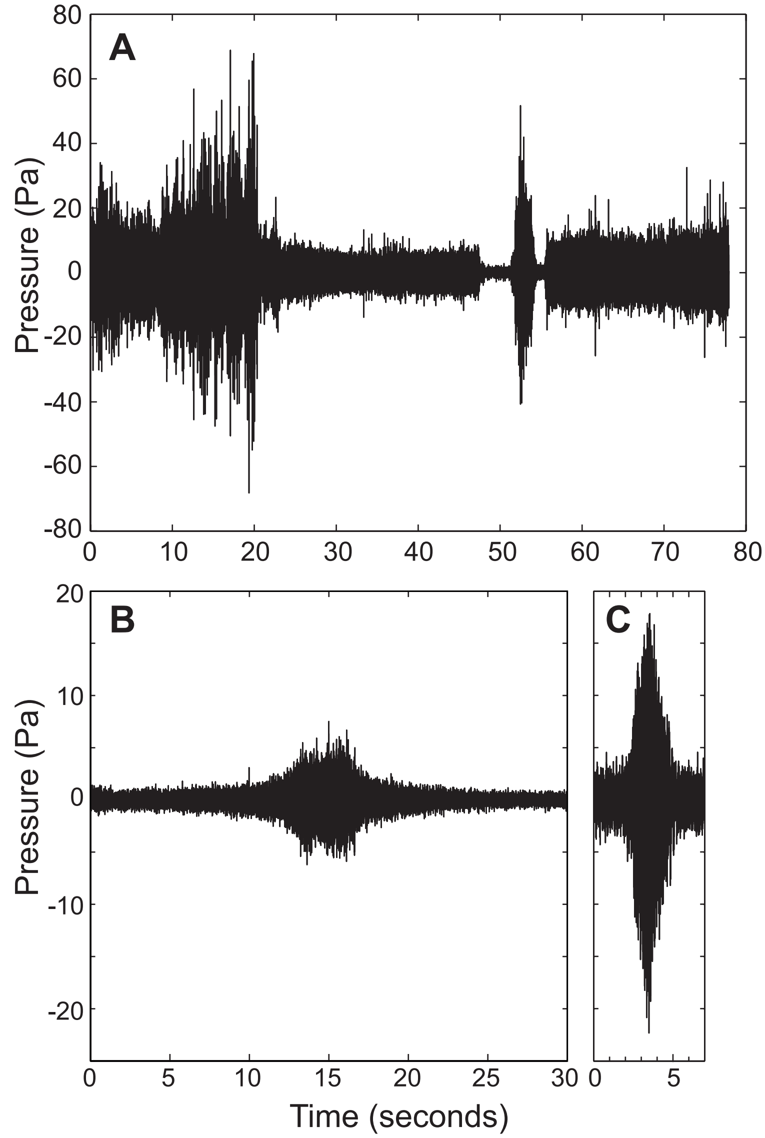

FIGURE 3: Typical sound pressure time series, showing received sound pressure (in pascals) *vs.* time for three underwater recordings. (***A***) Eighty seconds obtained while the tug *Leo* maneuvered the gravel barge *Katie II*. *Leo*'s stern was 140 m from the hydrophone at the beginning of this section and 120 m at the end. The lowest SPLs (right before and after the spike beginning at second 52) correspond to the tug idling. (***B***) Thirty seconds obtained during the overflight of a DC-10 at 90º during takeoff from Anchorage International Airport. The airplane was audible during this entire section. (***C***) Seven seconds obtained during the overflight of an F-15 fighter jet at 90º, right before landing at Elmendorf AFB. Note the higher background levels (compared to ***B***). The jet was only audible underwater during approximately three seconds.

Frequency composition was determined by calculating the sound pressure spectral density by Fourier analysis, using the Blackman-Harris minimum three term window (Harris 1978). The averaging time for such measurements was 8.5 s. The transform length was one second. With windowing, the spectral resolution was 1.7 Hz with 1-Hz bin separation. Transforms were overlapped by 50% and therefore sixteen power spectral densities were averaged for each 8.5-s measurement.

Airplane overflights were analyzed similarly, but because of the variability in the duration of the overflights (see Figure 3, ***B*** and ***C***), the sample length (and therefore averaging time) was either 2.5, 4.5 or 8.5 seconds. These samples were centered on the peak of the sound pressure time series and included most of the visible portion of the overflight on the sound pressure time series[1]. The transform length was one second, the spectral resolution was 1.7 Hz with 1-Hz bin separation and transforms overlapped by 50%.

The recordings of a Boston Whaler and Avon rubber boat were analyzed by averaging over 1.5-s samples. This was necessary because of the high speed of travel of the vessels (14 - 16 m/s).

To show how received levels varied with distance from the activity, root-mean-square (rms) broadband levels were plotted against range from the dominant source. These plots are based on the series of sound recordings at varying distances along a given transect. Interpretation of these data is complicated by variability of the sources within and between recordings, and by the likely contribution of sound from more than one sound source. Nevertheless, the "received level vs. range" plots give an estimate of the highest levels received at several distances during the activity studied. In addition, where appropriate, spectral analyses of the dominant sounds are included.

A tone was identified when the sound pressure spectral density level (SPSDL) for a given frequency was greater than the SPSDL for both adjacent frequencies, and at least 5 dB above the nearest minimum SPSDL at a lower frequency.

Broadband microphone data were A-weighted (and expressed in dBA referred to 20 μPa) to allow comparisons with common airborne sounds described in the literature. A-weighting applies a frequency-dependent weighting factor to the sound in accordance with the sensitivity of the human ear; therefore frequencies below 1 kHz and above 6 kHz are de-emphasized (Kinsler *et al.* 1982, Kryter 1985). One-third octave band data were not A-weighted and are expressed in dB re 20 μPa.

A simple propagation model was fitted to broadband levels received by both the hydrophone and microphone in order to develop equations that characterize propagation loss underwater and in air. The model used was based on logarithmic spreading loss:

Received level (**RL**, dB re 1μPa) [2] $= A + B \cdot \log(R)$, where R is range in m. Eq. (1)

1. The choice of sample length had, within reason, very little effect on broadband levels. For example, for short overflights (less than 5 seconds in duration) the difference in broadband level using a 2.5 or 4.5 s sample was always less than 1 dB and often less than 0.5 dB.
2. The units dB re 1 μPa were used for underwater sound pressure levels; units for in-air sound pressure levels are dB (or dBA, depending on whether the data were A-weighted) re 20 μPa.

In this equation, the constant term (*A*) is the hypothetical extrapolated received level at a distance of 1 m based on far-field measurements. The estimated "*A*" value is useful mainly as a basis for comparison with other sound sources operating in the same region. Expected values for the spreading loss term (*B*) are -20 dB/tenfold change in distance for spherical spreading (such as occurs in the open ocean for isovelocity profiles far from surface, bottom or other boundaries) and -10 dB/tenfold change in distance for cylindrical spreading (such as occurs in shallow water, where sound reflecting off the surface and bottom combine to diminish the logarithmic rate of spreading loss by half). Spreading loss terms exceeding -20 dB/tenfold change in distance are possible with shallow sources and / or receivers (Richardson *et al.* 1995b).

4.0 Results

4.1 Airplane Overflights

4.1.1 Underwater Measurements

Airplane overflight recordings were made on August 21 from two locations, one seaward of Anchorage International Airport (ANC) and the other seaward of Elmendorf Air Force Base (AFB). These recording locations are indicated in Figure 2 as blue stars. Fifteen commercial aircraft were recorded while taking off from ANC; seven of those fifteen recordings were detectable on the sound pressure time series and / or audible on the hydrophone recordings, and were subsequently analyzed. Similarly, eleven F-15 military jets were recorded while landing at Elmendorf AFB; of those, two were audible or detectable and analyzed. The reason only a fraction of the overflights were audible on the hydrophone recordings has to do with characteristics of sound transmission across the air / water interface. These are explained in more detail in the Discussion section.

Broadband (10 - 20,000 Hz) levels of underwater sound are presented in Figure 4 for these nine aircraft overflights as well as for ambient sound levels at both airports. “Ambient” samples for both airports in this analysis are samples during which there were no airplane overflights. The ambient level at Elmendorf AFB is higher than at ANC primarily because of the proximity to the Port of Anchorage (Fig. 2). The “construction and shipyard noise” value shown in Figure 4 comes from a section of the recording at ANC during which banging from construction work, engine noises and other sounds noticeably increased the broadband levels, despite the absence of an aircraft overflight at that moment. The mean and s.d. (standard deviation) values for the overflights shown in Figure 4 were 118.4 ± 5.7 dB re 1 μPa (n = 7) for ANC and 128.0 ± 9.0 dB re 1 μPa (n = 2) for Elmendorf AFB. The maximum values recorded were 124 dB re 1 μPa for a departing DC-10 straight overhead and 134 dB re 1 μPa for a landing military jet straight overhead.

One-third octave band levels underwater for three selected commercial aircraft and one military F-15 jet, illustrated in Figure 5, show that jet sounds are broadband in nature, extending up to 5 kHz and higher. The absence of rotary wings and propellers lead to a general lack of tones at low frequencies, but turbines will create tones at high frequencies, in the kHz order. The peak at the one-third octave band centered at 2500 Hz for a Boeing 747 (red triangles in Fig. 5) could be due to a tone originating from the jet’s turbines. Compared to the commercial aircraft, one-third octave band levels for an F-15 fighter jet (Fig. 4) shows notably higher SPLs at frequencies above 150 Hz. An ambient recording (i.e. taken with no aircraft overhead) at the ANC site is also shown for comparison. The peak at 25 Hz is of unknown origin.

Figure 6 shows underwater narrowband spectra for an F-15 fighter jet and a commercial DC-10, both passing overhead (90°), as compared to an ambient sample from the Elmendorf AFB recording site. The jet sounds are broadband in nature with most of the

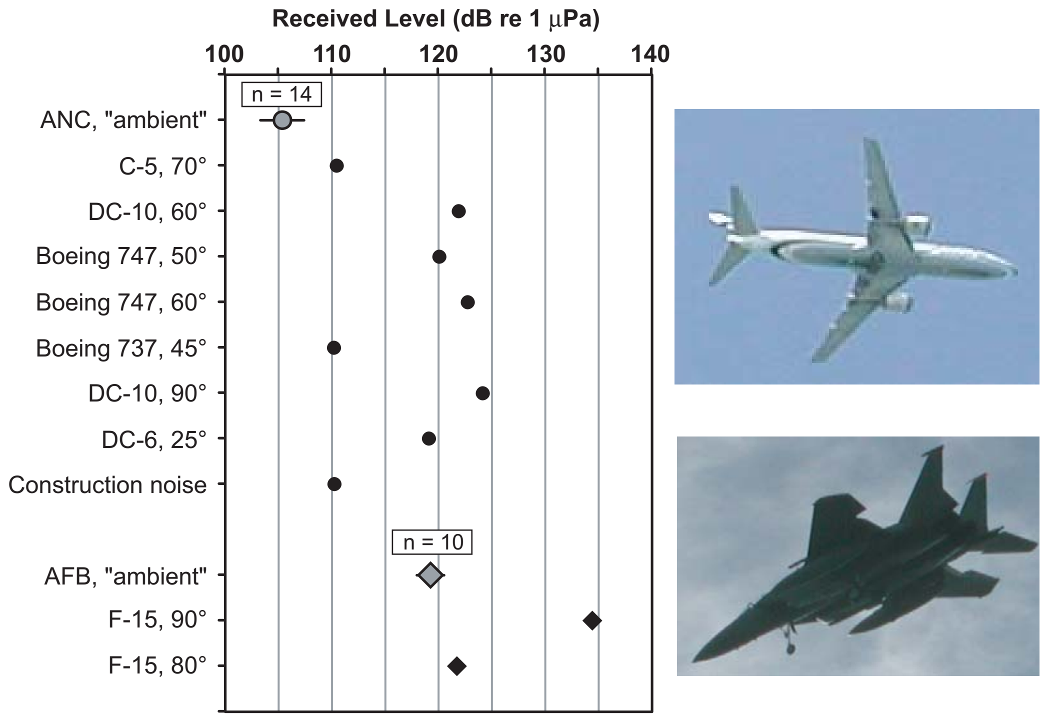

FIGURE 4: Broadband (10 - 20,000 Hz) levels of underwater sound associated with Anchorage International Airport (ANC) and Elmendorf Air Force Base (AFB). Planes were taking off at ANC and landing at the AFB. Each sample shown is a different aircraft. Ambient levels are means (± one s.d.) of several 8.5-s samples taken while no airplanes were landing or taking off. The sample size is indicated above the means.

energy below 2 kHz; for frequencies above 4.5 kHz, ambient sound levels at Elmendorf AFB exceed those produced by a DC-10 taking off from ANC.

4.1.2 In-Air Measurements

A-weighted broadband (20 - 18,000 Hz) levels of in-air sound are presented in Figure 7 for ten commercial aircraft and ten military jet overflights, as well as for ambient sound levels at both airports. For Elmendorf AFB the standard deviation bars are smaller than the symbol and are therefore not visible. Again, “ambient” samples in this analysis are samples during which there were no airplane overflights. The mean and s.d. values for the overflights shown in Figure 7 were 84.7 ± 6.6 dBA re 20 µPa (n = 10) for ANC and 88.0 ± 5.7 dBA re 20 µPa (n = 10) for Elmendorf AFB. The maximum values were 95 dBA re 20 µPa for a Boeing 747 at 60 degrees elevation and 94 dBA re 20 µPa for three military jets nearly overhead.

One-third octave band levels in air for both commercial and military jets are shown in Figure 8, and are compared to ambient levels at both airports. One-third octave band levels were similar for all aircraft shown, with most of the energy between 100 and 1,000 Hz and dropping off steeply between 3 and 10 kHz. There was more variation in the commercial jets, due to the broader range of airplane types (piston-driven propellers to turbojets) and sizes (small business jet to Boeing 747).

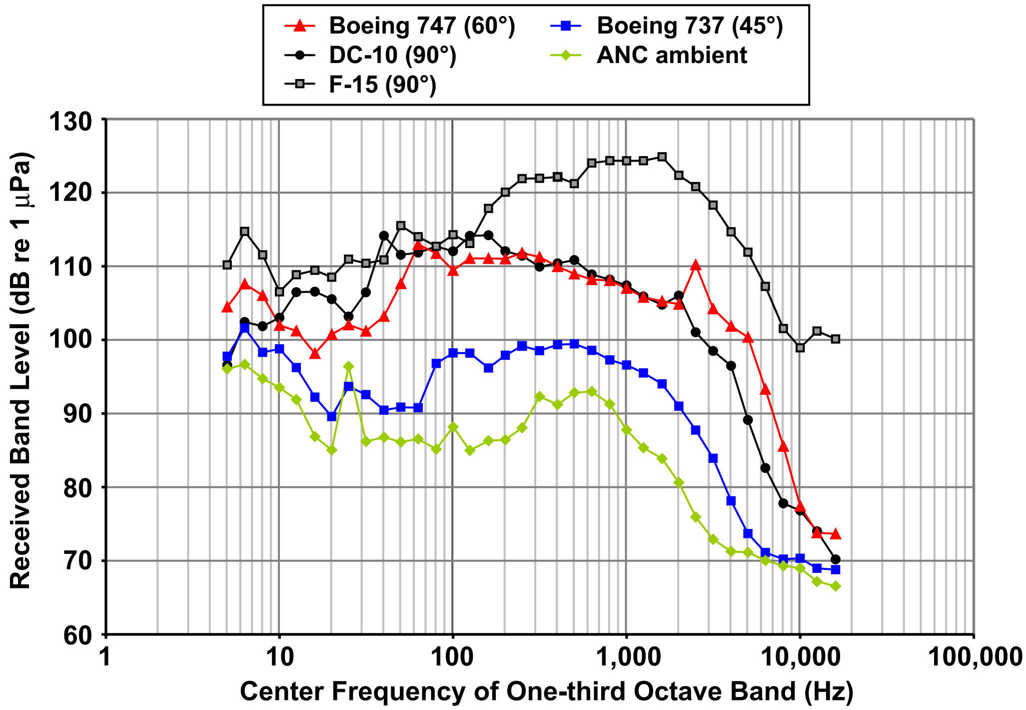

FIGURE 5: One-third octave band levels underwater for three types of commercial jets (red triangles, blue squares and green diamonds), an F-15 fighter jet (gray squares) and an ambient sample (filled circles) taken seaward of Anchorage International Airport (ANC), 21 Aug. 2001.

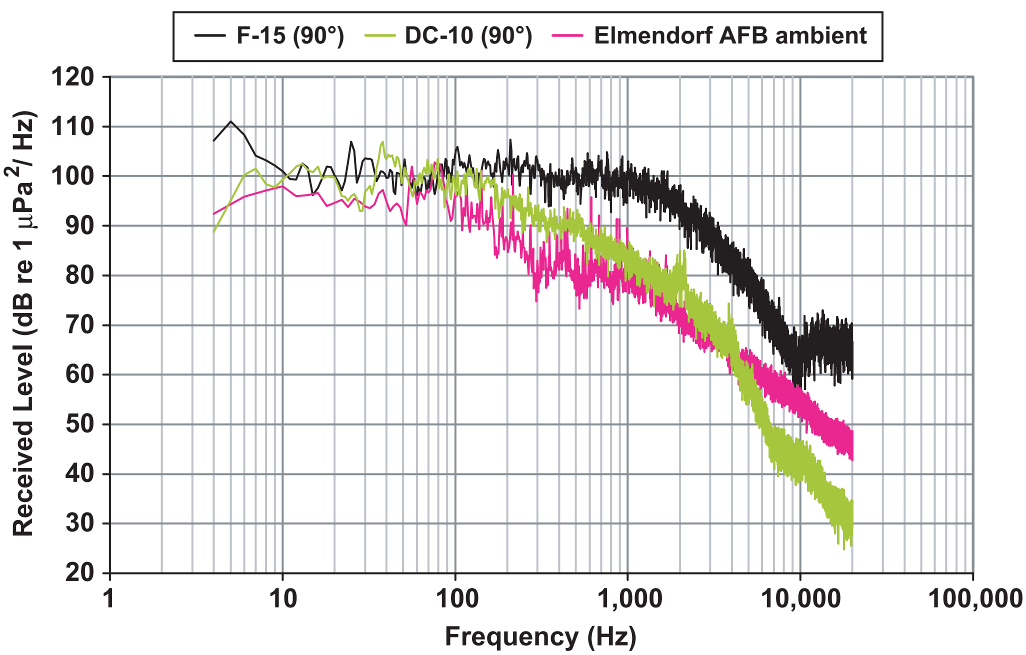

FIGURE 6: Underwater narrowband spectra (4 - 20,000 Hz) for an F-15 fighter jet about to land at Elmendorf AFB (black line), a DC-10 overhead right after take-off from ANC (green line) and an ambient sample seaward of Elmendorf AFB (pink line), 21 Aug. 2001.

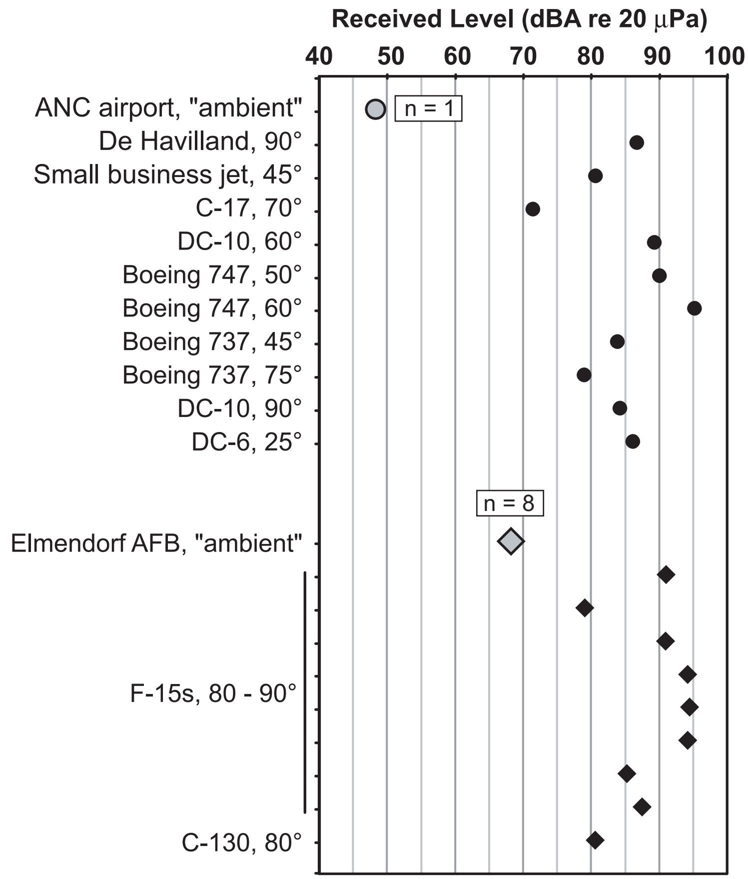

FIGURE 7: A-weighted broadband (20 - 18,000 Hz) levels of in-air sound associated with Anchorage International Airport (ANC) and Elmendorf AFB. Planes were taking off at ANC and landing at the AFB. Each sample shown is a different aircraft. The ambient level at Elmendorf AFB is a mean (± one s.d.) of eight 8.5-s samples taken while no airplanes were landing or taking off (the s.d. bars are smaller than the symbol size). Elevation angles are shown for the overflights.

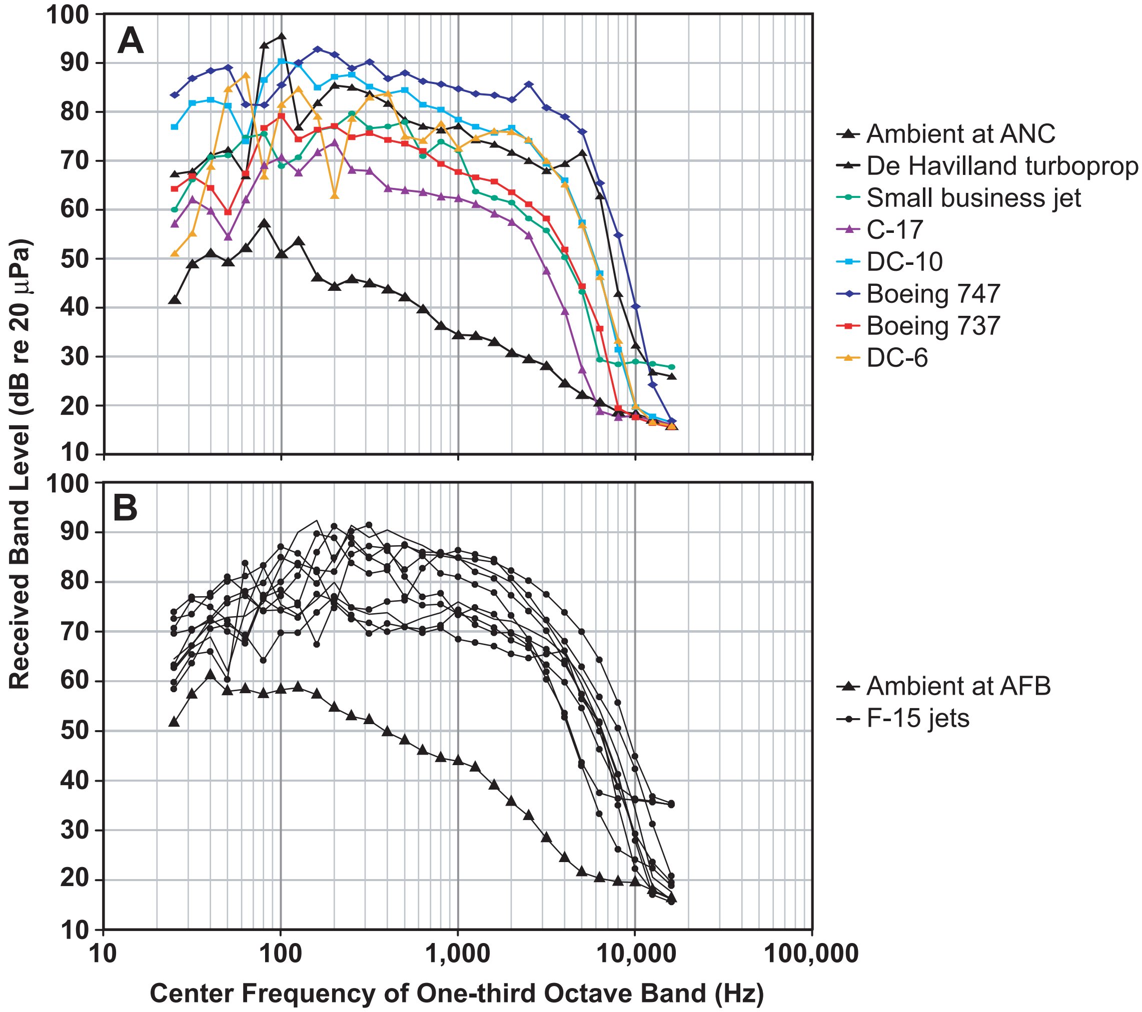

FIGURE 8: One-third octave band levels in air for various types of aircraft, 21 Aug. 2001. (***A***) Commercial jets at Anchorage International Airport (ANC) and (***B***) military F-15 jets at Elmendorf AFB.

4.2 Sounds from the *Phillips A* Oil Platform

4.2.1 Underwater Measurements

The *Phillips A* oil platform, shown in Figure 9, is located in the western part of Cook Inlet (filled black circle in Fig. 2). The platform was accessed on 22 August 2001 with the M/V *Stellar Wind*, a 650 ton tractor tug based in Anchorage, 85 feet long by 30 feet wide and with a 12 foot draft. Recordings were made at six locations, <400 m to 19 km from the platform (see Table 2; pink diamonds in Fig. 2). Weather conditions were close to ideal, with sea state 1/2 to 1 and a breeze from the south of 4 knots or less.

TABLE 2. Mean distance from *Phillips A* oil platform to six recording stations, and mean water depth at each of the stations. n.mi. = nautical mile.

Station	Mean distance to platform (km)	(n.mi.)	Mean water depth (m)	(feet)
1	0.34	0.18	27.6	91
2	1.2	0.64	23.2	76
3	1.4	0.76	24.5	80
4	3.0	1.6	24.4	80
5	9.9	5.4	23.3	76
6	18.8	10.1	27.4	90

FIGURE 9: *Phillips A* oil platform, Cook Inlet, AK, 22 August 2001.

Mean broadband (10 - 20,000 Hz) underwater SPLs for all six recording stations are presented in Figure 10. The sound propagation model (Eq. 1) was fitted to the data from all stations by least squares, and yielded a spreading loss term of -7.4 dB/tenfold change in distance. The highest level recorded was 119 dB re 1 μPa at a distance of 1.2 km. A nar-

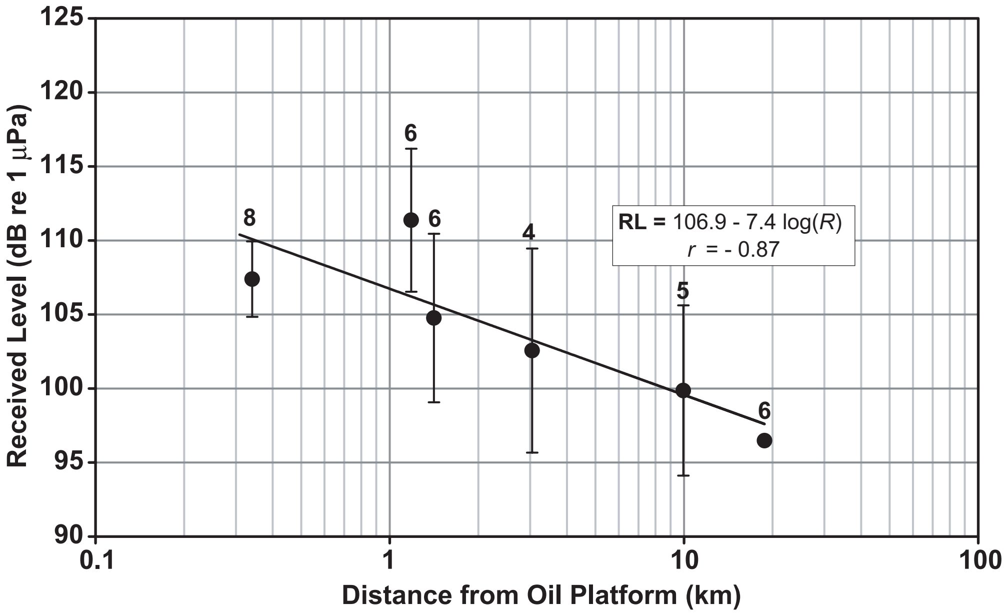

FIGURE 10: Mean broadband (10 - 20,000 Hz) levels of underwater sound at a range of distances from the *Phillips A* oil platform in Cook Inlet, AK. The logarithmic regression model shown was fitted to the recordings obtained up to 19 km from the oil platform. Means are shown ± one s.d.; if s.d. bars are not visible it is because they are smaller than the symbol size (i.e., at 19 km). Sample sizes are shown above the s.d. bars. 10 km = 5.4 n.mi. or 6.2 mi.

rowband spectrum from the closest station, depicted in Figure 11, shows a number of peaks at low frequencies, mainly below 200 Hz. Out of the 50 strongest tones identified in this sample, 42 (84%) were below 500 Hz. For comparison, a narrowband spectrum from the furthest station (6), 19 km from the oil platform, is shown in Figure 12. Even though overall levels have decreased compared to the closest station (Fig. 11), some of the same low-frequency peaks are visible (i.e., 30, 38 and 50 Hz).

One-third octave band levels underwater for all recording stations, shown in Figure 13, reveal a peak of noise around 80 Hz, which is most prominent close to the oil platform and decreases in intensity with distance. It is not present in the furthest recording (station 6 at 19 km). The “notch” at 30 - 40 Hz is attributed to sound propagation conditions related to the shallow water. The sounds at lower frequencies are probably arriving at the hydrophone via a “ground wave”, or through propagation in the bottom. Low frequencies are also most likely to be influenced by the tidal flow.

An analysis of the tones between 40 and 110 Hz revealed five tones which were present at all stations up to station 5 (340 m to 9.9 km from the oil platform), and which were present in over 50% of all 8.5-s samples analyzed (n = 33): 60, 68, 75, 90 and 105 Hz. The logarithmic sound propagation model (Eq. 1) was fitted by least squares to the mean SPL at each station for each of these tones. The spreading loss terms (*B* in Eq. 1) for the five tones were similar, ranging from -15.6 to -23.5 dB/tenfold change in distance (mean = -19.0) and the *r* values ranged from -0.84 to -0.99 (mean = -0.95). The reason these spreading loss values are higher than that computed using the broadband data alone (-7.4 dB/tenfold change in distance, see above) probably have to do with the fact that the

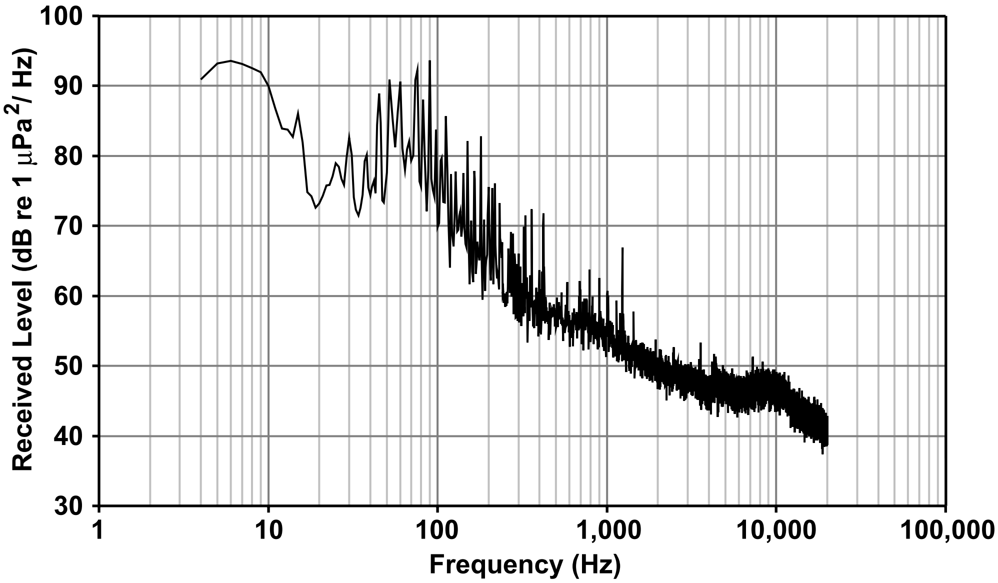

FIGURE 11: Narrowband spectrum (4 to 20,000 Hz) from a typical 8.5-s underwater sample from station 1 (340 m from the *Phillips A* oil platform), 22 August 2001.

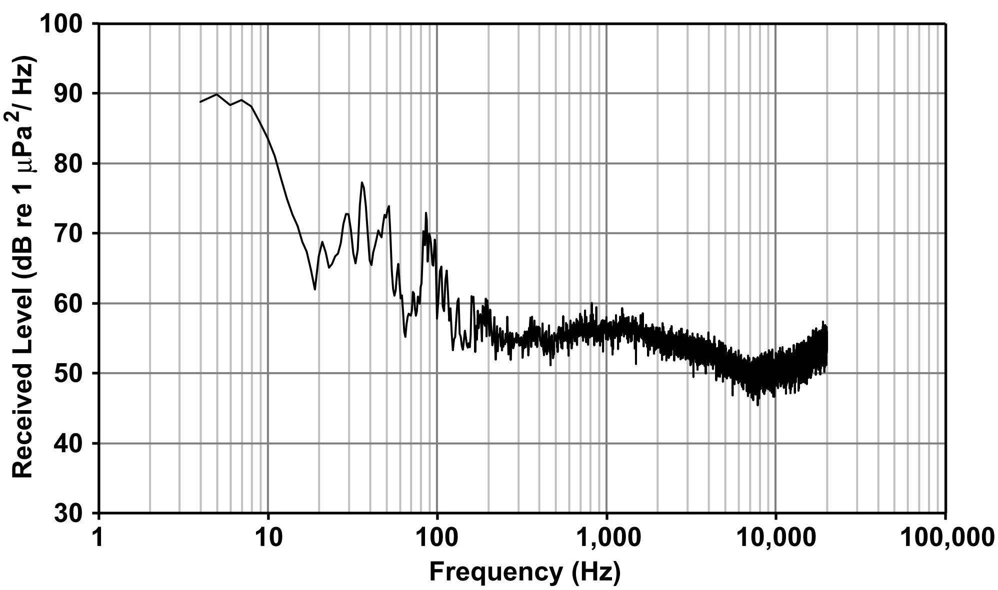

FIGURE 12: Narrowband spectrum (4 to 20,000 Hz) from a typical 8.5-s underwater sample from station 6 (19 km from the *Phillips A* oil platform), 22 August 2001.

broadband data include sound sources (such as tidal current flow, particularly at station 6) which were not related to the platform itself and could therefore have been increasing with distance from the platform.

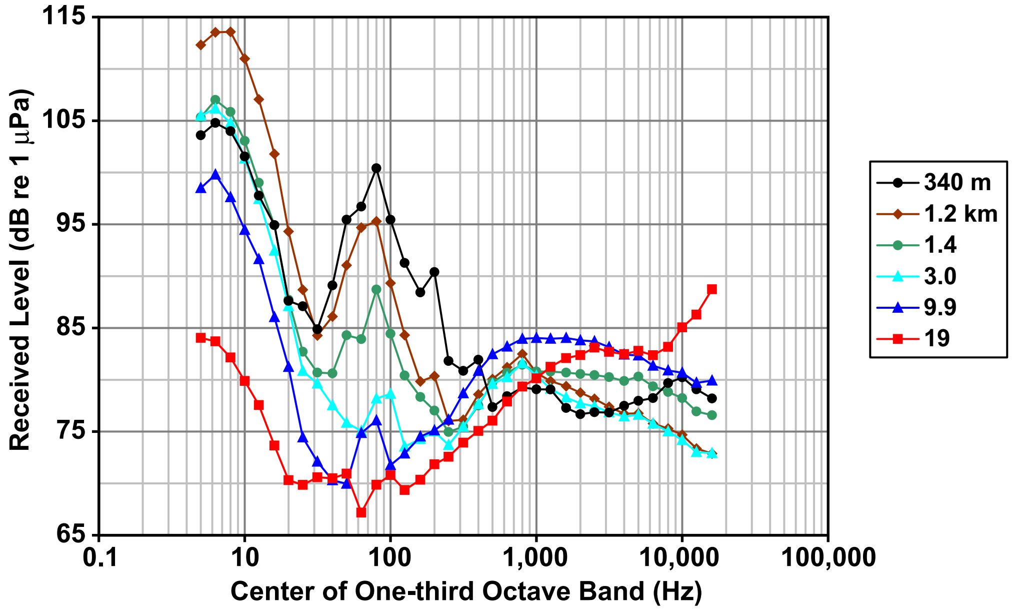

FIGURE 13: Mean received underwater sound pressure levels for one-third octave bands centered at frequencies of 5 - 16,000 Hz, for all recording stations from the *Phillips A* oil platform.

4.2.2 In-Air Measurements

Mean A-weighted broadband (20 - 18,000 Hz) airborne SPLs are shown in Figure 14 for all six recording stations. The highest level recorded was 65 dBA re 20 µPa at the closest recording station (#1), about 340 m from the oil platform.

Fitting the sound propagation model (Eq. 1) to the data from all stations by least squares yielded a spreading loss term of -16.5 dB/tenfold change in distance. One-third octave band levels for all recording stations, shown in Figure 15, reveal a peak of noise around 80 - 100 Hz, similar to the one which was seen on the hydrophone data at 80 Hz. This peak also decreased with distance from the oil platform but is less prominent than in the underwater recordings. A smaller peak at 200 Hz is also visible.

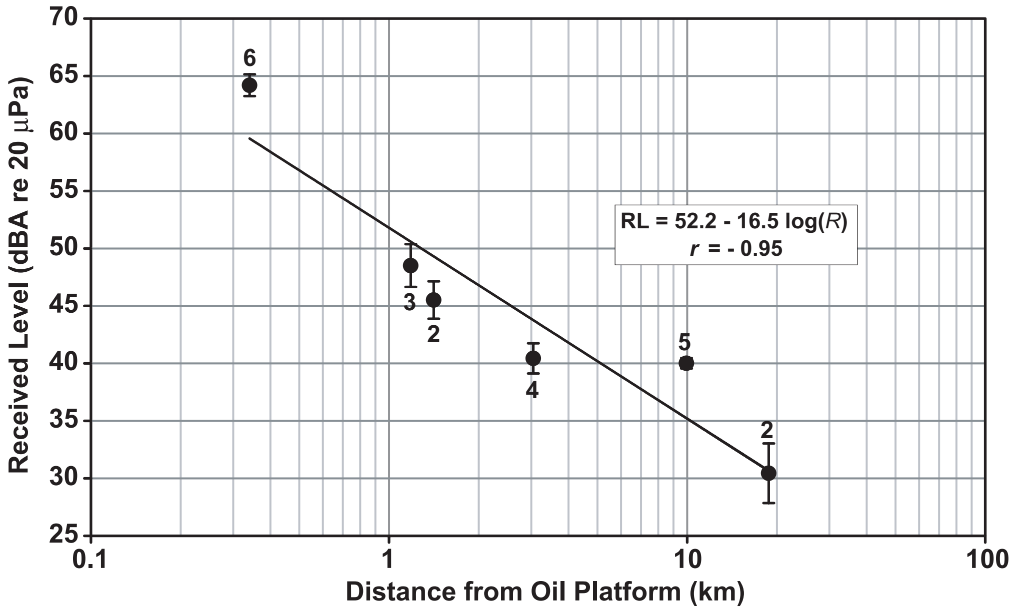

FIGURE 14: Mean A-weighted broadband (20 - 18,000 Hz) levels of in-air sound as a function of distance to the *Phillips A* oil platform in Cook Inlet, AK. The logarithmic regression model shown was fitted to the recordings obtained up to 19 km from the oil platform. Means are shown ± one s.d.; if s.d. bars are not visible it is because they are smaller than the symbol size. Sample sizes are shown above the s.d. bars.10 km = 5.4 n.mi. or 6.2 mi.

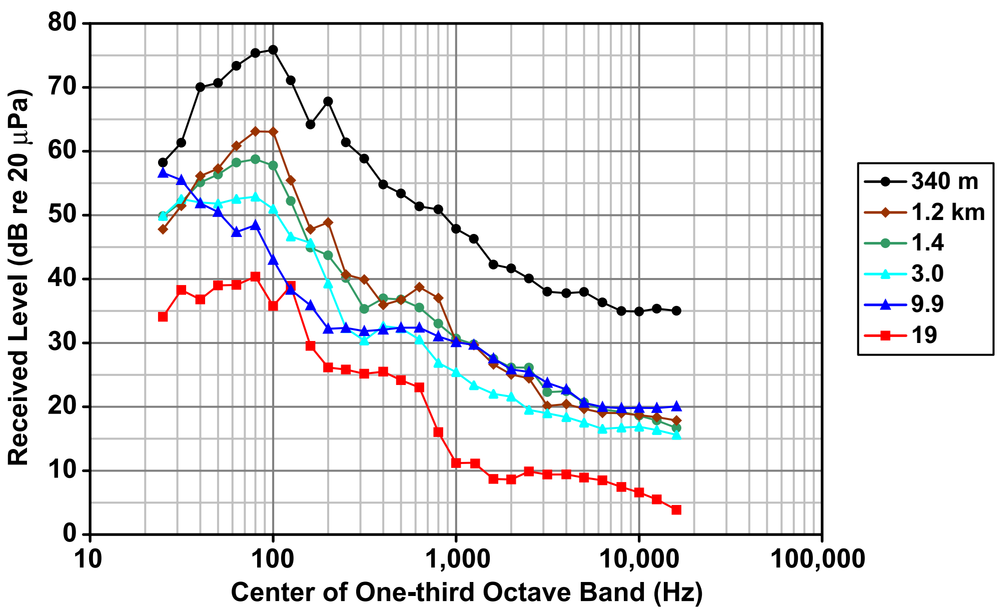

FIGURE 15: Mean received in-air sound pressure levels for one-third octave bands centered at frequencies of 25 - 16,000 Hz, for all recording stations from the *Phillips A* oil platform.

4.3 Sounds from Large and Small Vessels in Anchorage Harbor

4.3.1 Underwater Measurements

Seven recordings of the sounds produced by small and large vessels in Anchorage harbor were made on 21, 23 and 24 August 2001. These recordings were done opportunistically, except for those involving the Boston Whaler and Avon rubber boat. Recording locations are all shown on the insert of Figure 2 as green and purple triangles. Recorded sound sources included:

- the cargo-freight ship *Northern Lights* while docked in the harbor during loading or unloading (see Fig. 16); the cargo-bulk carrier *Emerald Bulker* while being held at the dock by two tugs immediately preceding its departure, and then during its departure from Anchorage harbor;
- the tug *Leo* while pushing the gravel barge *Katie II* towards a dock, and then while maneuvering and holding the barge against the dock;
- drive-by at full speed of two small craft, a Boston Whaler and an Avon rubber boat. The Boston Whaler ("Justice" model, length 6.4 m = 21 feet) was powered by a 250 hp Johnson 2-cycle engine. The Avon rubber boat (length 5.4 m = 18 feet) had a rigid hull and was powered by an 80 hp Yamaha 4-cycle engine.

FIGURE 16: The stern of the cargo-freight ship *Northern Lights*, docked in Anchorage harbor. Note the military jet making its final approach towards Elmendorf AFB. Beluga whales were seen near the stern, close to shore.

Broadband (10 - 20,000 Hz) underwater SPLs as a function of distance to the presumed sound source are shown in Figure 17 for all the larger vessels. The highest SPL recorded was 149 dB re 1 μPa, about 100 m from the tug *Leo* while it was holding or maneuvering the gravel barge *Katie II* against a dock. Broadband levels obtained during that recording are well matched with those from the *Emerald Bulker*'s departure from the harbor. Similarly, values recorded from the *Northern Lights* (while docked) are close to those recorded while the *Leo* was pushing the gravel barge *Katie II*. The logarithmic sound propagation model (Eq. 1) was fitted by least squares to the four data sets which covered a range of distances of at least 200 m.

The resulting equations are:

Northern Lights, docked: **RL** = 133.5 - 4.5 log(*R*), *r* = - 0.83

Emerald Bulker leaving, stern aspect: **RL** = 188.8 - 21.0 log(*R*), *r* = -0.89

Leo pushing *Katie II*: **RL** = 163.8 - 17.4 log(*R*), *r* = -0.80

Leo docking *Katie II*: **RL** = 178.9 - 17.8 log(*R*), *r* = -0.74

where RL is the received level and *R* is the distance to the sound source in meters. The low spreading-loss term obtained for the *Northern Lights* is probably due to contamination from other sound sources in the harbor (see Discussion section).

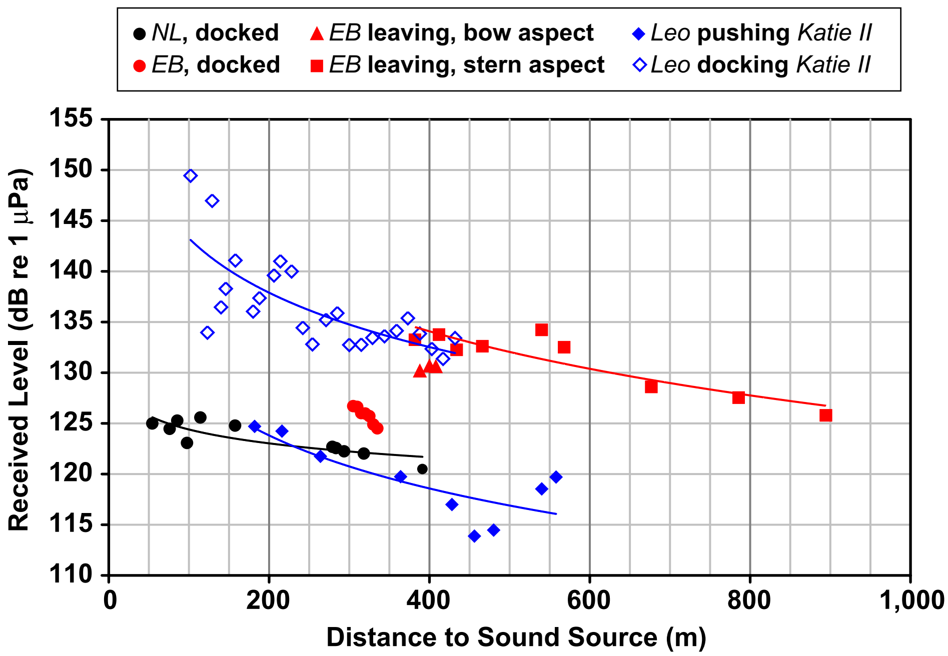

FIGURE 17: Broadband (10 - 20,000 Hz) underwater SPLs as a function of distance to sound source for various large vessels operating in Anchorage harbor. *NL* = *Northern Lights*, *EB* = *Emerald Bulker*. The equations for the logarithmic sound propagation models are given in the text. 500 m = 1640 feet.

During the recording of the *Northern Lights*, 4-6 beluga whales were seen within a few meters of the hull of the cargo-freight ship. Despite the proximity of the recording vessel to the whales no beluga vocalizations were heard on the recordings, and none could be detected by spectral analysis. The received broadband levels when the observations were made were in the vicinity of 125 dB re 1 µPa, which is probably sufficient to mask the weaker beluga whistles. Sound pressure levels in the 3 - 9 kHz range, in which beluga whistles were readily detectable at the Birchwood site (see below), were 30 dB higher than in the Birchwood recordings.

A narrowband spectrum from the recording of the tug *Leo* pushing the gravel barge *Katie II* is shown in Figure 18. Most of the sound energy is in the band 100 - 2000 Hz. A large peak is visible at 50 Hz and tones were detected at numerous multiples of 25 Hz (many of which are visible on the narrowband plot): 25, 100, 125, 151, 175, 201, 225, 251, 300, 326 Hz and so on up to 426 Hz. It is likely that the tug was at the source of the 25-Hz tone, which could have been a blade-turning rate. Blade-turning rates between 15 and 40 Hz have been recorded from River and Ocean-class tugs on the North Slope (Blackwell and Greene 2002). The dip in received levels for frequencies below about 400 Hz, and especially below 150 Hz, is indicative of the rapid attenuation of those frequencies in very shallow water - the water depth during the recording shown in Figure 18 was only about 7 m. The levels rise for frequencies below 100 Hz as "ground waves" contribute to the received levels.

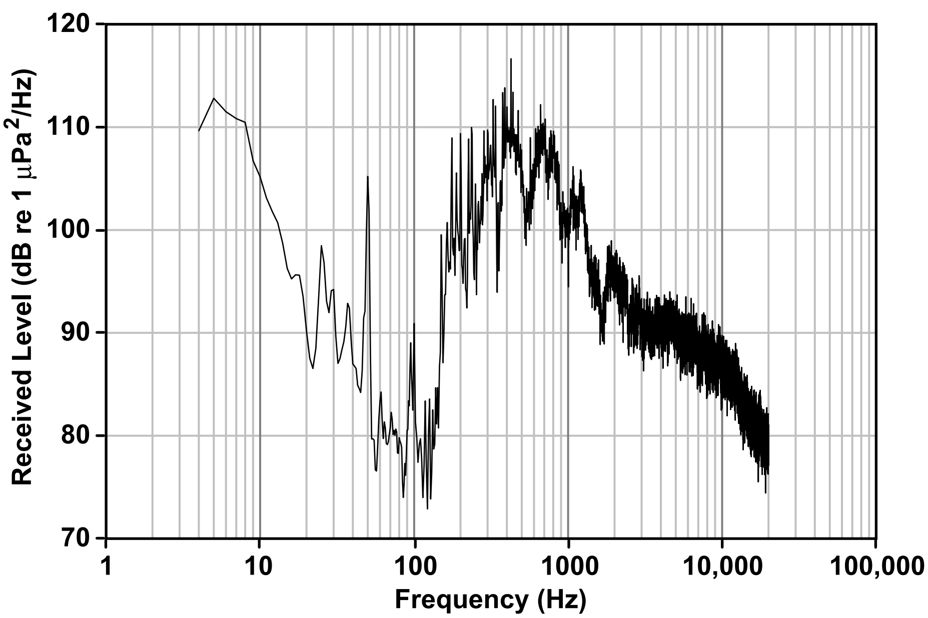

FIGURE 18: Underwater narrowband spectrum (4 to 20,000 Hz) from the recording of the tug *Leo* docking the gravel barge *Katie II*, 23 August 2000. The tug was about 188 m away from the hydrophone in this sample.

Broadband (10 - 20,000 Hz) underwater SPLs as a function of distance are shown for the two small craft, a Boston Whaler and an Avon rubber boat, in Figure 19. Both of these craft drove by the recording vessel at full speed during the recording. The highest recorded levels (at the closest point of approach = CPA) were 138 dB re 1 µPa at 13 m for the Boston Whaler and 142 dB re 1 µPa at 8.5 m for the Avon rubber boat. The logarithmic sound propagation model (Eq. 1) was fitted by least squares to the two data sets and yielded spreading loss terms of -7.8 and -14.0 dB/tenfold change in distance for the Boston Whaler and Avon rubber boat, respectively. The water depth during these recordings was about 30 m (98 feet). Ambient broadband levels are also shown in Figure 19 as dashed lines for comparison. These recordings were made several seconds or a few minutes before each vessel's drive-by.

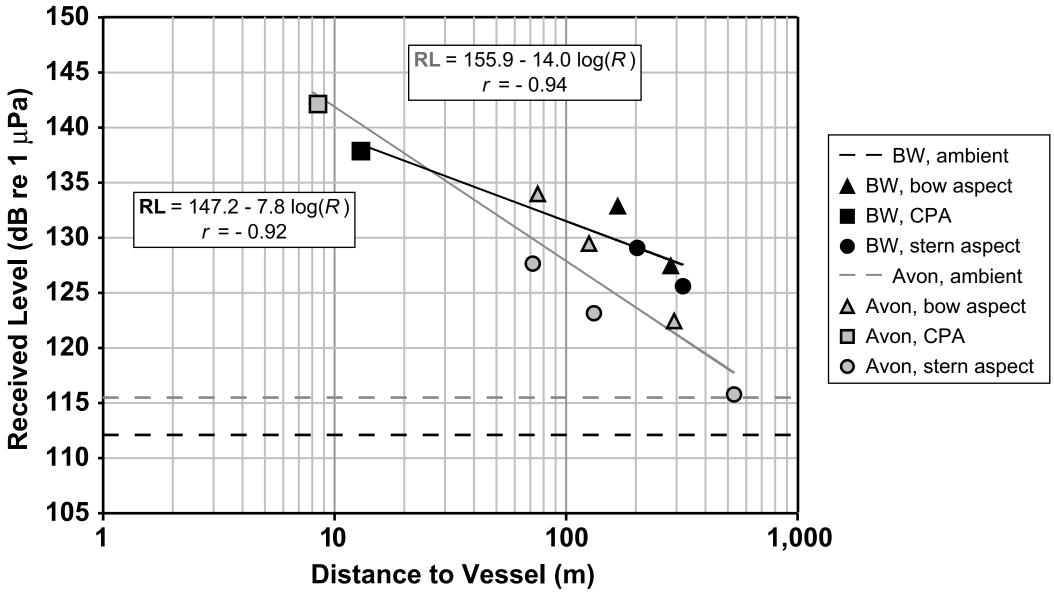

FIGURE 19: Broadband (10 - 20,000) underwater levels as a function of distance during drive-by by a Boston Whaler (BW, black symbols) and an Avon rubber boat (grey symbols). CPA = closest point of approach. The logarithmic spreading loss model is shown for each vessel. Ambient levels are shown for comparison as dashed lines (see text).

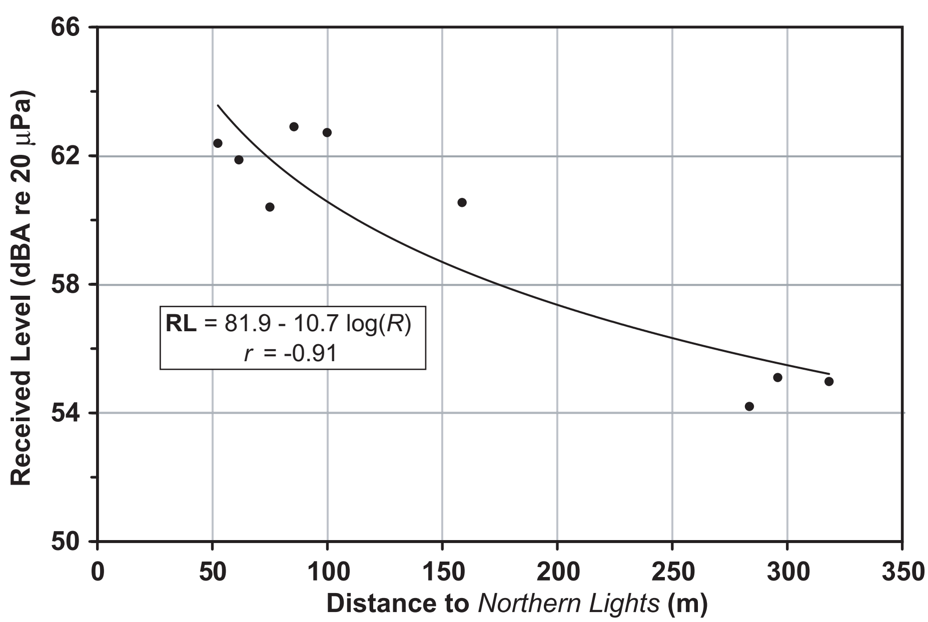

FIGURE 20: A-weighted broadband (20 - 18,000 Hz) levels of sound in air as a function of distance to the *Northern Lights*, while docked in Anchorage harbor. The logarithmic regression model shown was fitted by least squares. 200 m = 656 feet.

4.3.2 In-air Measurements

In-air recordings of vessels in Anchorage harbor were only obtained for the cargo-freight ship *Northern Lights* while docked. A-weighted broadband (20 - 18,000 Hz) levels as a function of distance from the *Northern Lights* are shown in Figure 20. The logarithmic sound propagation model (Eq. 1) was fitted by least squares to the data set, resulting in a spreading loss term of -10.7 dB/tenfold change in distance. As for the underwater recording obtained at the same time (shown in Fig. 17), contamination from other sound sources probably contributed to making this value somewhat lower than expected.

4.4 Ambient Sound Levels in Areas Removed from Industrial Activity

4.4.1 Underwater Measurements

In order to document naturally-occurring underwater sounds, recordings were made in five locations in Cook Inlet and Knik Arm, some of which are known to harbor beluga whales at certain times of the year (recording locations are shown as red inverted triangles in Fig. 2). These locations were not in the immediate vicinity of industrial activities and are more representative of "natural" ambient sound levels. The locations and their respective water depths are presented in Table 3.

TABLE 3. Mean water depth for recording locations in areas removed from industrial activity.

Location	Mean water depth (m)	(feet)
Mouth of Little Susitna River	8.8	29
Between Fire Island and mouth of Little Susitna River	19.5	64
Birchwood	6.7	22
Mouth of Eagle River	11.9	39
North of Point Possession	47.4	156

All five recordings except the one north of Point Possession were made at high tide on August 23. Wind speed was 4-10 knots at the mouth of the Little Susitna River, 10-14 knots between Fire Island and Little Susitna River and 1-3 knots at Birchwood and Eagle River. Recording conditions were very good at Birchwood and Eagle River (sea state 0-1), good at the mouth of the Little Susitna River (sea state 2) and somewhat rough for rubber boat-based recordings at the site between Little Susitna River and Fire Island (sea state 2-3). This is because waves slapping on the side of the boat create a certain amount of self noise which cannot be separated from the ambient sounds. The recording north of Point Possession was made on August 22 during the incoming tide, when the rate of change was highest (about 7 feet / hour). Weather conditions were close to ideal, with sea state 1/2 to 1 and a breeze from the south of 4 knots or less.

Underwater broadband (10 - 20,000 Hz) SPLs are presented in Figure 21 for these five locations. In addition, three ambient levels which have been presented in the previous sections of this report are also shown for comparison. These include ambient levels at the Anchorage airport and Elmendorf AFB locations (recorded while no airplanes were landing or taking off; blue stars in Fig. 2), and the Anchorage harbor ambient recordings (which preceded the small craft drive-by experiments; orange triangles in the Fig. 2 insert).

Underwater narrowband spectra are shown in Figure 22 for three contrasting locations: Birchwood, located northeast of Anchorage up the Knik Arm (Fig. 22A, pink line), the Anchorage harbor area (Fig. 22A, black line), and the location north of Point Posses-

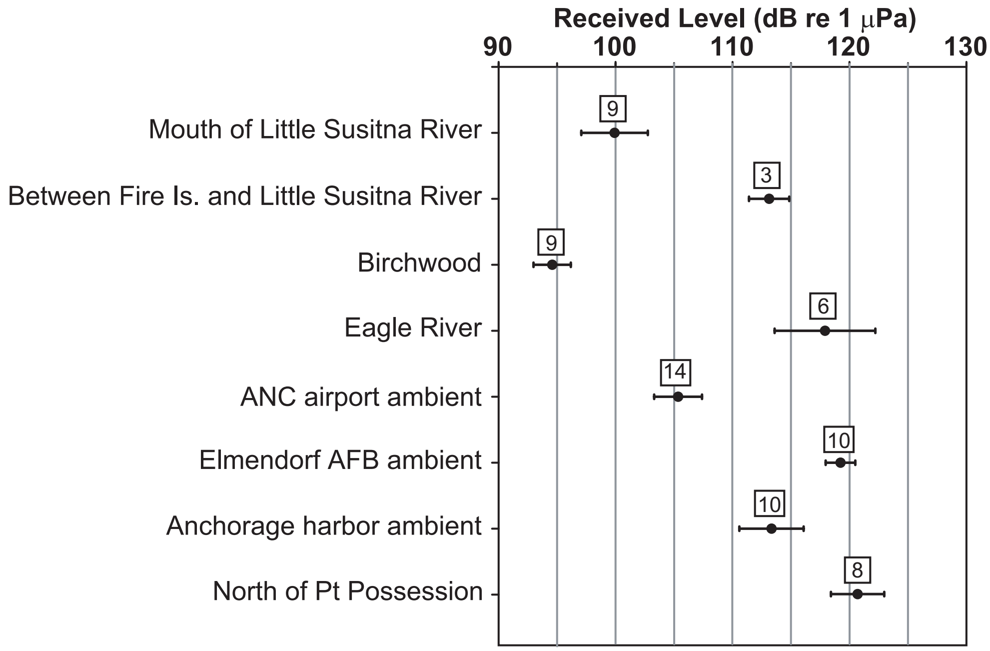

FIGURE 21: Broadband (10 - 20,000 Hz) levels of ambient underwater sound for eight locations in Cook Inlet and Knik Arm, with varying levels of proximity to industrial activities (see text for details). Values shown are means ± one s.d. The number of 8.5-s samples used for each mean is indicated above the mean.

sion (Fig. 22B, green line). Birchwood was the quietest location (see Fig. 21) and also the only one at which beluga whales were heard. The whales produced a variety of whistles and noisy vocalizations which contributed to the peaks in sound levels between 200 Hz and somewhat over 1 kHz visible in Figure 22***A***. The sounds that were heard on the Anchorage harbor recording included a variety of noises of the type that can be expected in an area with construction, boat traffic, loading and offloading of vessels. Sound levels are higher at all frequencies and include two prominent peaks at 30-40 Hz and 60 Hz. These can be linked to power generation and industrial activities in general. The location north of Point Possession had the highest broadband level of all the locations shown in Figure 21 and reached 124 dB re 1 μPa. During that recording the tide was coming in and the sounds it generated predominated in the recording and were audible by the field crew in air and underwater. The lack of prominent tones over most of the frequency range (i.e., atonality of the sound source) and "bell" shape at higher frequencies (500 - 20,000 Hz) is characteristic of this type of sound. The source of the peaks at 21, 29 and 38 Hz is not known.

4.4.2 In-air Measurements

In-air recordings were only made at the location north of Point Possession on 22 August. Mean A-weighted broadband (20 - 18,000 Hz) levels were 40 dBA re 20 μPa. This is below "ambient" in-air measurements made at the ANC location (48 dBA re 20 μPa, see Fig. 7), the Elmendorf AFB location (68 dBA re 20 μPa, see Fig. 7), in Anchorage harbor in the vicinity of the *Northern Lights* (54-63 dBA re 20 μPa, see Fig. 20) and at the three closest stations to the *Phillips A* oil platform (45-65 dBA re 20 μPa, see Fig. 14).

Tide noises likely contributed to the in-air broadband levels at that station as they were audible, albeit faintly, by the field crew.

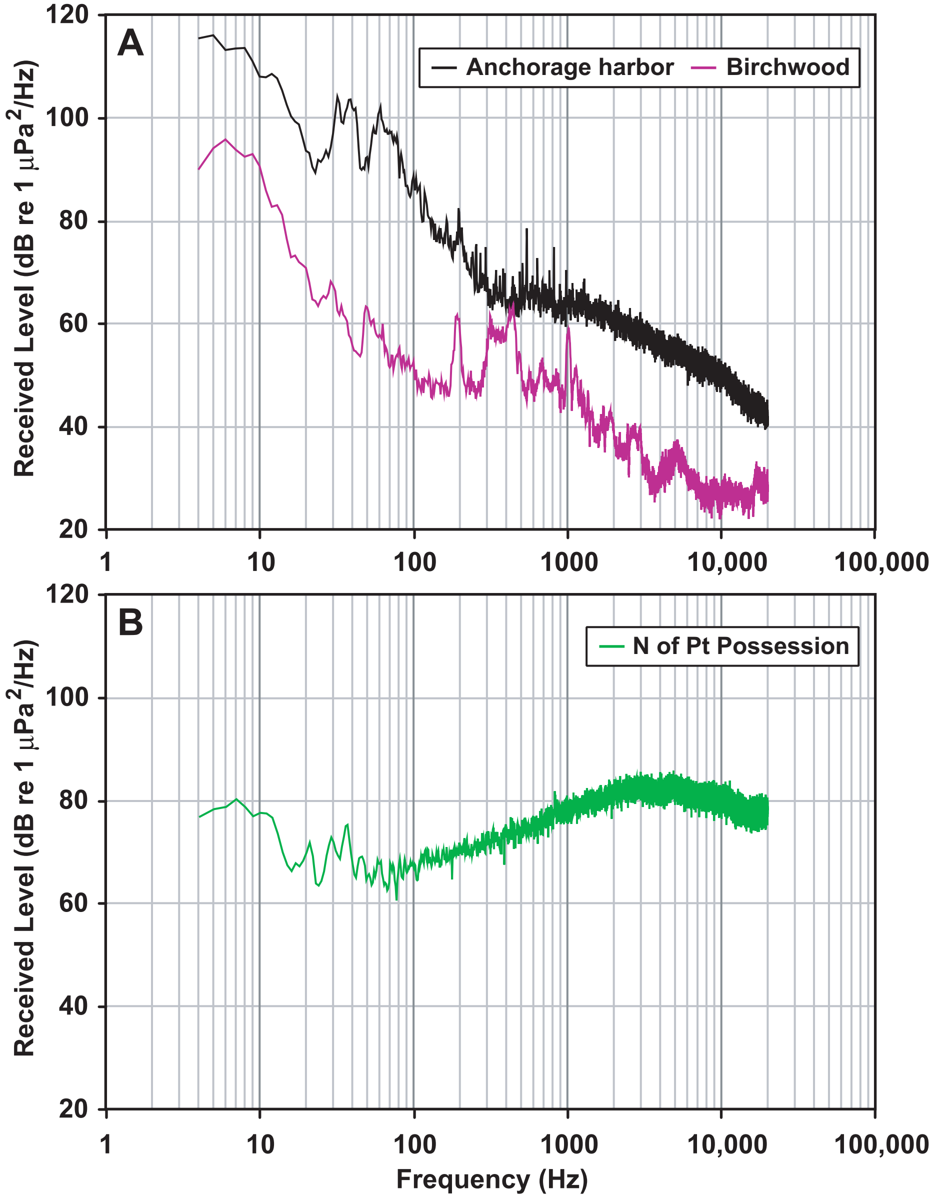

FIGURE 22: Narrowband underwater spectra (4 to 20,000 Hz) from typical 8.5-s samples. ***(A)*** Anchorage harbor (24 Aug.) and Birchwood (23 Aug.); ***(B)*** North of Point Possession (22 Aug.).

5.0 Discussion

5.1 Airplane Overflights

5.1.1 Underwater Measurements

During transmission of sound from air to water, a large amount of the acoustic energy is reflected. In the case of an overhead sound source, such as an aircraft, most (but not all) of the sound at angles greater than 13 degrees from the vertical is reflected and does not penetrate the water (the area of maximum transmission under an aircraft can therefore be visualized as a 26 degree cone with the aircraft at the apex). This is particularly true if the conditions are calm, the water is deep or the water is shallow but with a nonreflective bottom (see Richardson *et al.* 1995b). When waves are present, they will provide suitable angles for additional transmission, but only above certain frequencies (Lubard and Hurdle 1976). Water depth and bottom conditions (i.e., whether the bottom is reflective to sound or not) also have an important influence on the propagation of aircraft sound underwater.

The thirteen degree critical angle predicted by Snell's law (see above) explains why only a fraction[1] of aircraft overflights, both at ANC and Elmendorf AFB, were audible or even detectable on the underwater sound pressure time series. However, some overflights were audible at angles below 77 degrees (= 90 - 13) and in these cases it is likely that the hydrophone picked up reflected sound waves that had bounced between bottom and surface in the rather shallow waters (80-100 feet) seaward of the airports. Surface water choppiness during the recordings would also have led to improved transmission into the water beyond that predicted by Snell's law alone. The water depth at both airport recording locations was similar, 80-100 feet, but aircraft were landing at Elmendorf AFB whereas they were taking off at ANC. Takeoff is a time of maximum power output for the aircraft and should therefore correspond to maximum sound production, but at ANC we were positioned farther from the runway than at Elmendorf AFB and therefore the recorded aircraft were at higher altitudes, leading to greater distances between the source of sound and the water. A practical consequence of the "26 degree rule" is that aircraft at higher altitudes will be audible for a longer time since the base of the cone (see previous paragraph) will be wider. Aircraft altitude during take-off or landing will naturally also depend on its size and type. In the overflights we recorded at both airports the (estimated) altitude of the aircraft varied between about 400 and 2000 feet (122 to 610 m). The effective overflight time on the sound pressure time series for our data was indeed shorter for jets landing at Elmendorf AFB (about 3 seconds as shown in Fig. 3***C***) than for jets taking off at ANC (usually 10 to 20 seconds, see Fig. 3***B***). Finally, the detectability of an overflight will also be limited by ambient sound levels underwater. Ambient broadband levels at Elmendorf AFB were about 15 dB higher than at ANC (Fig. 4, also visible in Fig. 3***B*** and ***C***) and may account in part for the low rate of detectability of the military jets. These

1. 7/15 at ANC = 47%; 2/11 at Elmendorf AFB = 18%.

higher broadband levels were most likely due to the close proximity of Anchorage harbor where both shipyard and construction activities were noted.

With all these variables, comparisons and predictions become difficult. Nevertheless, broadband levels recorded underwater all fell in the range of 110 to 125 dB re 1 μPa for the commercial aircraft and up to 135 dB re 1 μPa for one F-15 military jet.

Figures 4 and 5 confirm that aircraft sounds are broadband in nature and extend over a wide range of frequencies. Because of the lack of rotary wings and propellers few tones are visible at lower frequencies, but turbines can produce tones at higher frequencies (above 500 Hz). In summary, the received level underwater will depend on the type of aircraft (jet versus propeller plane; also, older jets are often noisier), flight phase (landing or taking off), size (larger aircraft are usually noisier), altitude (lower is noisier but duration of overflight is shorter), angle to the listener, water depth, sea state (sound is transmitted into the water at wider angles if some waves are present) and bottom type (i.e., reflective or not).

Aircraft disturbance to beluga whales is the best documented amongst toothed whales; a review and extensive bibliography is given in Richardson *et al.* 1995b. Common reactions include longer dives, shorter surface intervals and temporary displacement (i.e., Bel'kovich 1960, Kleinenberg *et al.* 1964). The frequency with which these reactions take place varies with several factors, such as the distance to the aircraft (see below), the activity of the whales (i.e., feeding whales less prone to disturbance) and the group composition (i.e., single whales more prone to disturbance); there are also strong individual variations between the animals (Richardson *et al.* 1995b). Patenaude *et al.* (2002) found that 86% of belugas reacted to a Bell 212 helicopter at altitudes ≤ 150 m and lateral distances ≤ 250 m. Fixed-wing aircraft (Twin Otter) overflights elicited many fewer reactions, and mainly during low-altitude flights (≤ 182 m). Peak sound levels were 2.5 dB higher at 3 m than 18 m depth, and the authors concluded that both mid-frequency sound components and visual clues could play a role in eliciting beluga whales' reactions to aircraft.

5.1.2 In-air Measurements

Broadband in-air measurements made at the two airports were comparable, as shown by the mean values (84.7 ± 6.6 dBA re 20 μPa at ANC vs. 88.0 ± 5.7 dBA re 20 μPa at Elmendorf AFB). For comparison, A-weighted sound levels of 80 - 90 dBA re 20 μPa correspond to the sounds of a heavy truck at 64 km/h (40 m.p.h.) at 15 m (49 feet) or a blender at the operator's position. A-weighted sound levels of 90 - 100 dBA re 20 μPa correspond to the sounds of a power mower at the operator's position or the cockpit of a light aircraft (Kinsler *et al.* 1982). One-third octave band levels in air, shown in Fig. 8, were similar between the commercial and military jets and matched findings from the underwater measurements.

5.2 Sounds from the *Phillips A* Oil Platform

5.2.1 Underwater Measurements

Mean underwater broadband levels recorded in the vicinity of the *Phillips A* platform, shown in Fig. 10, did not level out within the range of our measurements, leading us to believe that we had not reached "background" values 10 km from the platform. However, the large amount of variability within each station, particularly stations 2 to 5 (1.2 to 9.9 km from the platform) make this statement more difficult to support based on the broadband data alone. For the 30 - 200 Hz frequency band, the one-third octave band data (Fig. 13) show increasing levels with decreasing range; this increase we attributed to the oil platform. Gales (1982) reported peak spectrum levels for two oil production platforms in the range 50 - 200 and 100 - 500 Hz, respectively, which matches our findings. Power generation in general tends to produce tones in this range, particularly at 60 Hz and multiples thereof. The peak in our data, centered at about 80 Hz, decreased with distance from the platform and is indistinguishable at station 6, 19 km away. It is therefore reasonable to assume that in sea state conditions similar to the ones we experienced on 22 August, noises from the *Phillips A* oil platform would have reached background levels within a distance of 20 km. Sea state and wind have an important influence on sound levels underwater, but they were minimized in these recordings as the conditions we experienced were close to ideal (SS 1/2 - 1, wind <4 knots).

Underwater noise from structures such as the *Phillips A* oil platform is expected to be relatively weak because of the small surface area in contact with the water, namely the four legs (Richardson *et al.* 1995b). In addition, the machinery is placed on the deck of the platform, well above the water. However, vibrations from the machinery through the columns and into the bottom may be notable, accounting in part for the high levels seen at low frequencies (<30 Hz) in Figure 13.

The spreading loss term obtained from the mean broadband data, -7.4 dB/tenfold change in distance, is lower than expected. This could be due in part to variability in the sound sources other than the platform itself, such as tide noises or sounds from vessels, etc. Ground wave energy from the platform could also account for the lower loss rate of the broadband sound. The spreading loss terms obtained from using the tone data alone, -15.6 to -23.5 dB/tenfold change in distance, are closer to what one would expect for this type of situation.

5.2.2 In-air Measurements

Mean A-weighted in-air measurements at the closest station were 64 dBA re 20 μPa (Figure 14). According to data compiled by Kinsler *et al.* (1982), this is comparable to the sound of a vacuum cleaner at the operator's position or an air-conditioner at 6 m (20 feet). Background levels seem to have been reached by station 4, 3 km from the platform, with station 6 being unusually quiet.

5.3 Sounds from Large and Small Vessels in Anchorage Harbor

5.3.1 Underwater Measurements

The spreading loss terms obtained from the departure of the *Emerald Bulker* (-21.0 dB/tenfold change in distance) and the two recordings involving the tug *Leo* and gravel barge *Katie II* (-17.4 and -17.8 dB/tenfold change in distance) are very similar to each other (especially considering the fact that Anchorage harbor with its numerous sound sources is far from an ideal recording environment) and are reasonable for this situation (see Fig. 17). The recording of the *Northern Lights* while docked yielded a lower-than-expected spreading loss term, most likely because of contamination from other sound sources and because the source (the ship) is so long compared to the nearer distances. Indeed the entire harbor was one extensive sound field. Drifting away from one sound source often meant drifting into the zone of influence of another, particularly for sound sources that were not much higher than ambient levels.

Actual sound levels at distance 1 m (source levels) cannot be computed reliably from far-field measurements, but a large ship such as the *Emerald Bulker* will likely produce broadband source levels on the order of 180 dB re 1 μPa-m (i.e., at 1 m) while underway, as suggested by the data in Figure 17. Source levels of that magnitude are common for large ships such as container ships, supertankers or icebreakers (Richardson *et al.* 1995b).

The narrowband spectrum of the tug *Leo* (Fig. 18) is fairly typical for vessels of that size and larger, with prominent tones at low frequencies (<100 Hz) and harmonics of these tones. Most of the sound energy is below 1 to 2 kHz. This narrowband spectrum also reveals the "high-pass filter" effect of shallow water on low frequencies. In other words, there is a sharp decline in the received levels of frequencies below about 200 Hz because those frequencies transmit poorly in the very shallow water in which the recording was made (7 m = 23 feet). Bottom traveling sounds (ground waves) contribute to the higher levels around 5-10 Hz.

The drive-by recordings of the Avon rubber boat resulted in a more reasonable spreading loss term (-14.0 dB/tenfold change in distance) than the same experiment performed with a Boston Whaler (-7.8 dB/tenfold change in distance). The recording of the Boston Whaler was done over a shorter distance and with fewer distance readings available to us. These distance readings are very important but are difficult to obtain with accuracy since the vessels are traveling at 14-16 m/s. At 200 m the 250 hp Johnson 2-cycle engine (on Boston Whaler) produced broadband sound levels about 6 dB higher than the 80 hp 4-cycle Yamaha engine (on Avon rubber boat). This is reasonable considering the Yamaha engine was both lower-power and fired half as often per revolution. Based on these recordings the source level for the 80 hp Yamaha engine is probably close to 150 dB re 1 μPa-m. Note that the source of the sound is primarily the propeller, which is relatively shallow. The Lloyd mirror effect (Urick 1983) severely limits good coupling of sound from shallow sources at low frequencies.

5.3.2 Beluga Whale Observations

The observation of beluga whales very close to the stern of the docked *Northern Lights* seems to indicate that the animals were not particularly bothered by the sounds produced by the cargo-freight ship. To illustrate how these sounds relate to the animal's hearing threshold we compared one-third octave band levels from the recording of the *Northern Lights*, at a distance of 85 m, with two beluga audiograms (see Figure caption for sources). Threshold hearing levels are generally measured with tones. To allow for the critical ratio[1] of an animal's perception of broadband sound, broadband (not tonal) sounds are compared in one-third octave bands to the hearing thresholds.

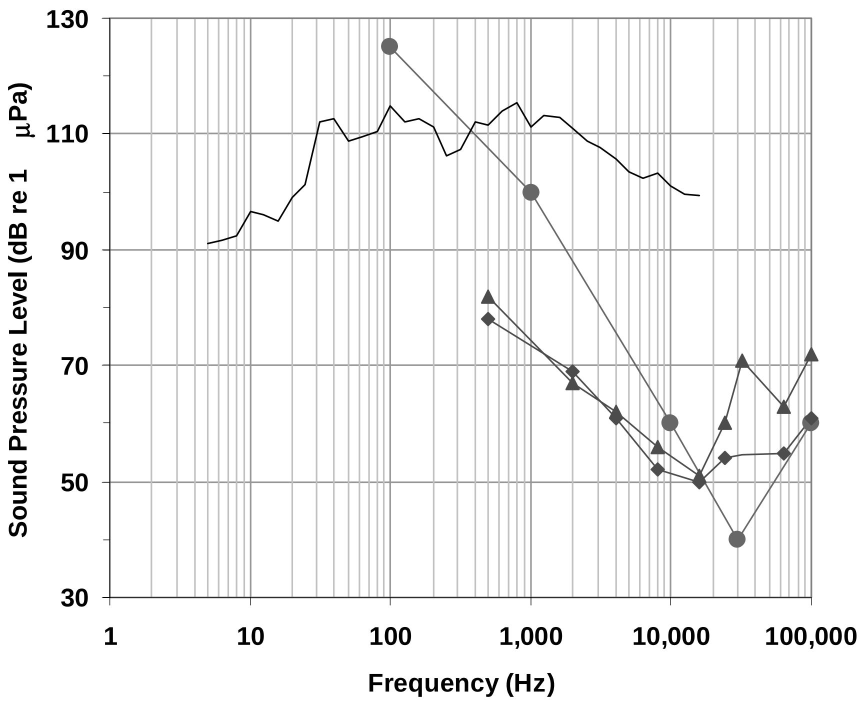

FIGURE 23: One-third octave band levels for an 8.5-s sample recorded 85 m from the *Northern Lights*. Blue dots are average threshold levels for beluga whales from several sources (White *et al.* 1978, Awbrey *et al.* 1988, Johnson *et al.* 1989), summarized in Richardson *et al.* (1995b). The red symbols show more recent data collected by Ridgway *et al.* (2001) on two different animals (red triangles = Noc and red diamonds = Muk) at a depth of 5 m.

It is important to remember that the one-third octave band levels shown for the *Northern Lights* in Figure 23 are for a distance of 85 m from the ship. At closer distances SPLs will likely be higher, but not by much (on the order of ~3 dB), since spreading-loss equations for extended sources computed from far-field data are not valid for received level predictions in the near-field. Based on the older sources for threshold hearing levels (White *et al.* 1978, Awbrey *et al.* 1988, Johnson *et al.* 1989), a beluga whale at a distance

1. The critical ratio is the amount by which a pure-tone signal must exceed the spectrum level background noise in order to be audible (Richardson *et al.* 1995b).

of 85 m from the *Northern Lights* would not be expected to hear the lower frequency sounds produced by the ship (i.e., below ~350 Hz). However, this is not supported by the more recent data collected by Ridgway *et al.* (2001). Regardless, given the proximity of the belugas to the *Northern Lights*, it seems even the higher frequency sounds were insufficiently strong to cause the whales to avoid the ship.

The frequency of maximum sensitivity for beluga whales, shown in Figure 23, is ~30 kHz for the older sources (see above) and ~16 kHz for the recent data collected by Ridgway *et al.* (2001). Even though this is well above the frequency range of most industrial noise (Richardson *et al.* 1995b), the level for the one-third octave band centered at 16 kHz (comprising the frequency range 14.2 - 17.8 kHz) in the *Northern Lights* recording is substantial, nearly 100 dB and ~50 dB above the belugas' hearing threshold at those frequencies (according to the Ridgeway *et al.* audiograms). For comparison, the equivalent one-third octave band value for the site with the highest broadband background level - Point Possession during the incoming tide - was 115 dB. At the Birchwood site, which had the lowest broadband background levels, the received level for the one-third octave band centered at 16 kHz was 66 dB.

5.3.3 In-air Measurements

A-weighted broadband SPLs at various distances from the cargo-freight ship *Northern Lights* ranged from 54 to 63 dBA re 20 μPa (Fig. 20). To put these levels in perspective, they are comparable to the sounds produced by light traffic at 30 m (98 feet; Kinsler *et al.* 1982).

5.4 Ambient Sound Levels in Areas Removed from Industrial Activity

The mean ambient underwater broadband levels shown in Figure 21 span a fairly wide range, from 95 to 120 dB re 1 μPa. The variation within each recording, however, was generally small. The two quietest locations (Little Susitna River and Birchwood) were in areas removed from the close proximity of industrial activity, but so was the loudest (north of Point Possession), whose elevated broadband levels we attributed to the turbulence and bottom pebble motion associated with the incoming tide. Broadband levels for the location between Fire Island and Little Susitna River were probably artificially elevated as there was a fair amount of noise on the recording from wave slap against the sound boat hull. It is not surprising that the recording location seaward of Anchorage International Airport was the quietest of the “industrial” locations, as it is somewhat removed from Anchorage itself and the harbor. The ambient Anchorage harbor recording was taken further from shore than the Elmendorf AFB ambient (which was also within the harbor area); this could explain the lower values.

Burgess and Greene (1999) made true ambient recordings in the Beaufort Sea in 1998 with Autonomous Seafloor Acoustic Recorders (ASARs), away from boat traffic or other industrial sounds. The water depths were on the order of 40 m. These recorders were deployed on the bottom and recorded continuously, with a sampling rate of 1 or 2 kHz for days to weeks. The bandwidth of the data reported by Burgess and Greene is narrower than that reported here: 20 - 1,000 Hz, *vs*. 10 - 20,000 Hz in the present study, so it is necessary to compare the equivalent values. The contribution of industrial sound to the 1,000 - 20,000 Hz band is very small, but the same is not true for the 10 - 20 Hz band. Reducing the bandwidth of the Cook Inlet measurements to 20 - 1,000 Hz reduced the mean broadband underwater values for the four "non-industrial" sites by 7 - 10 dB. These mean broadband (20 - 1,000 Hz) values are shown below:

- Mouth of Little Susitna River: 92 dB re 1 μPa
- Between Fire Island and Little Susitna River: 102 dB re 1 μPa
- Birchwood: 88 dB re 1 μPa
- Eagle River: 107 dB re 1 μPa
- North of Point Possession: 104 dB re 1 μPa

The minimum, 5th percentile, 50th percentile (= median), 95th percentile and maximum broadband (20 - 1,000 Hz) values reported by Burgess and Greene (1999) were 68, 79, 99, 114 and 132 dB re 1 μPa. Therefore, ambient levels at Birchwood and the mouth of the Little Susitna River fall right between the 5th and 50th percentiles, ambients sounds at the location between Little Susitna and Fire Island fall very close to the median, and sound levels at the Point Possession and Eagle River locations fall between the median and 95th percentile in the Burgess and Greene (1999) data.

A comparison of the narrowband spectra from the Birchwood and Anchorage harbor sites (see Fig. 22A) shows roughly a 20 dB increase in sound pressure levels across all frequencies at the "industrial" site. In addition, there are several peaks at low frequencies (<100 Hz) and a smooth decrease with frequency above 1 kHz. This is fairly typical of most industrial noise as well as oceanic traffic, which primarily affects frequencies below 1 kHz. Numerous whistles at frequencies around 9 kHz were identified in the Birchwood recordings, as well as a variety of other sounds produced by the whales. These contributed to the peaks seen in Figure 22A at frequencies of roughly 200 - 1,000 Hz. Beluga whales are known to produce sounds in a wide range of frequencies, from about 250 Hz to 20 kHz (Sjare and Smith 1986a, b), and as high as 120 kHz when echolocating (Au 1993).

The recording north of Point Possession yielded some of the highest broadband levels, up to 25 dB above the quietest station (Birchwood, see Fig. 21). While no man-made sounds could be detected by listening to the recording with earphones, and no tones associated with the *Phillips A* platform could be identified (the platform was 33 km or 18 n.mi. away), tide noises were predominant (these noises can be compared to that of gravel being poured from a dump truck). The narrowband spectrum plot (Fig. 22B) shows an unusual emphasis on higher frequencies, specifically 1 to 10 kHz. For example, the received level for the one-third octave band centered at 5 kHz was about 16 dB higher than the Anchorage harbor recording and 40 dB higher than the Birchwood recording. No other recordings during this study showed such a relative increase in sound levels at higher frequencies, except to some extent the recording at station 6, 19 km from the *Phillips A* platform (see Fig. 12 and Fig. 13). This recording was made about 45 minutes before the recording north of Point Possession and the tide was starting to come in, reaching its fastest rate of change (about 7 feet / hour) by the time of the Point Possession recording.

Tidal noise at frequencies of 10 Hz and above might arise from at least three mechanisms (Urick 1983): (1) noise from turbulent flow in the water; (2) noise from water flow over the bottom, especially if there are loose rocks that can roll around; and (3) noise from the surface if the flow induces surface roughness. At Cook Inlet we observed surface roughness due to tidal flow, although the scale was small, not exceeding 10 - 20 cm peak-to-peak. The sounds heard on the hydrophone were those of rolling gravel, consistent with the bottom substrate description of "cobbles, pebbles, silt and clay" (see section 2.1). We were probably hearing the motion of the cobbles and pebbles. Water turbulence was most likely at infrasonic frequencies. A fourth noise mechanism is self-noise from the hydrophone and its suspension, but this is unlikely since we used an effective fairing to eliminate cable strumming and did not detect any strumming noises on the recordings. There was undoubtedly a certain amount of flow noise around the hydrophone itself.

5.5 Potential Effects of Ice Cover on Sound Levels in Cook Inlet

Sea ice is found over Cook Inlet for 6-8 months of the year (October-November to March-April, Mulherin *et al.* 2001) and could have an effect on the ambient and waterborne industrial sounds. The ice might increase the noise from turbulence due to tidal flow, increasing the low-frequency ambient levels. Thermal cracking from air temperature changes could increase ambient noise at high frequencies (Milne and Ganton 1964). Wind over the ice will create noise from the turbulence. Similar noises are created by wind over open water, but the lack of wave noise in ice-covered conditions may result in lower noise levels for a given wind speed. Finally, industrial sounds may not propagate as well at the lowest frequencies as a result of the ice effectively decreasing the water depth, thereby raising the low-frequency cut-off. The reduced boat traffic in ice-covered areas is likely the largest indirect effect of ice cover on sound levels.

5.6 Measured Noise Levels and Beluga Hearing Sensitivity

A comparison between the Cook Inlet sounds presented in this report and information from published studies on beluga whale hearing leads to the following comments. Beluga whales are able to hear an unusually wide range of frequencies, covering most natural and man-made sounds. Where their hearing is keenest (10 - 100 kHz) is above the frequency range of most industrial sounds. At low frequencies (<100 Hz) beluga hearing threshold levels were comparable to or below one-third octave band levels recorded for most industrial activities reported in this study. Beluga whales were observed in the Anchorage harbor area travelling slowly within a few meters of the hull and stern of the moored cargo-freight ship *Northern Lights* (see Fig. 16). During this observation the whales did not seem bothered by visual or auditory stimuli from the ship or other harbor activities. In Cook Inlet, Burns and Seaman (1985) described beluga whales as often tolerant of the frequent passages of large vessels. Belugas have been seen near drillsites and close to operational artificial islands (Richardson et al. 1995b), as well as within 9 m of some production platforms in Cook Inlet (Gales 1982, McCarty 1982). In these cases the constant sound seemed nondisturbing to the whales. In areas where they are subjected to a lot of boat traffic beluga whales are thought to habituate and become tolerant of the vessels. Finally, they exhibit plasticity in their choice of call types, rates and frequencies in response to changes in the frequency distribution of their environment, i.e. approach of a vessel (Lesage *et al.* 1993) or transfer to another location with a different acoustic background "signature" (Au *et al.* 1985).

In contrast, beluga whales have been shown to react at extremely long ranges (35-50 km) to noise from ships and icebreakers underway in the Canadian Arctic (LGL and Greeneridge 1986, Cosens and Dueck 1988, Finley *et al.* 1990, Erbe and Farmer 2000). It is hypothesized that vessel noise has a stronger influence on belugas when the whales are confined by ice (LGL and Greeneridge 1986, Norton Fraker and Fraker 1982, Burns and Seaman 1985). The studies summarized in this and the previous paragraph demonstrate that beluga whales display an extremely wide range of reactions to anthropogenic sounds.

For pulsed sounds (i.e., pile-driving, explosions etc.) NMFS (2000b) has specified that cetaceans should not be exposed to rms levels (averaged over the pulse duration) exceeding 180 dB, but an equivalent reference value does not exist for continuous sounds (such as those described in this report). Very few studies have been able to determine the received level at which a free-ranging cetacean starts showing behavioral changes, but two such studies on beluga whales are summarized below. Richardson *et al.* (1991) reported overt reactions to playbacks of drilling noises by some belugas during spring migration past Point Barrow, starting at received broadband levels of ~112 dB re 1 μPa. The dominant frequencies were on the order of 200 Hz, where beluga hearing sensitivity is low. The whales' reactions were to slow down, mill or reverse course for several minutes, and then continue on their way. Reactions were seen 200 - 400 m from the sound projector, but some belugas passed the projector at a distance of 50 - 100 m. In another study, Richardson *et al.* (1995a) reported overt reactions to playbacks of icebreaker noises by some belugas during spring migration past Point Barrow. The whales in six of 17 groups approached within tens to hundreds of meters before showing a response. Received sound levels at the whales were estimated to be ~80 dB re 1 μPa in the one-third octave band centered at 5,000 Hz. The other 11 groups showed no obvious diversion but were exposed to about the same sound levels.

In addition to disturbing the animal and causing behavioral changes, increased sound levels can also have indirect effects, for example through auditory masking. A tone is masked principally by sounds at frequencies near the frequency of the tone. Therefore, the potential impact of auditory masking as a problem for beluga whales is diminished by the small amount of overlap between the frequencies produced by most industrial noise (<1 kHz) and the frequencies at which beluga whales call (0.26 - 20 kHz; Schevill and Lawrence 1949, Sjare and Smith 1986a, 1986b) and echolocate (40 - 60 kHz and 100 - 120 kHz; Au *et al.* 1985, 1987, Au 1993).

In conclusion, the following statements can be made:

1) None of the SPLs recorded in this study approached values that might be expected to injure belugas.

2) Based on a comparison of spectrum levels and beluga audiogram data, the industrial sounds present in Cook Inlet can certainly be heard by the whales. In some cases and

for certain frequencies, one-third octave band levels were as much as 50 dB higher than the whales' hearing threshold at the corresponding frequencies.

3) The variability in the responses of belugas to anthropogenic noise render generalizations meaningless, and a realistic "threshold level to disturbance" would probably have to be determined on a regional basis. Nevertheless, it seems that belugas in industrialized areas have to a large extent habituated to noises from ships and industrial activities, when compared to animals living in remote locations such as the high Arctic.

4) Based on the limited observation of two individuals in the harbor of Anchorage, at least some individuals do not seem disturbed by sounds such as those found right next to a large cargo-freight ship that was docked but with auxiliaries running.

5) There is a lack of information on (a) the types and intensities of sounds that lead to behavioral disturbance reactions in Cook Inlet belugas; (b) the long-term effects of repeated behavioral disturbances on a population of belugas in an industrialized area; and (c) the long-term effects of exposure to above-average sound pressure levels on beluga hearing. In light of this, we feel that the only way to better understand how the sounds recorded in this study affect Cook Inlet belugas on a daily and an individual basis is to obtain simultaneous information on the sounds the animals hear and the reactions (or lack thereof) that they trigger. With the constant progress of new tagging technologies, the easiest way to obtain this type of information would probably be to instrument selected individuals with acoustic recording tags.

5.7 Data Gaps

We believe that the measurements presented in this report provide a reasonable picture of the sound environment beluga whales can be subjected to in Cook Inlet during the summer, which corresponds to the season with most activity, particularly boat traffic. However, beluga whales have been seen in the central Inlet in winter (Moore and DeMaster 2000), and therefore measurements in conditions of ice cover may provide additional useful information.

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