Measurements of Underwater Noise in Eagle Bay of Knik Arm, Alaska due to Land-Based Explosions

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Summary

The underwater sound levels of land-based explosions from C4 detonations were measured over five days in October 2012 and June 2013. This report represents a combined summary of all data from both efforts. The objectives of this study were to (a) measure the received sound levels in water from explosions of varying sizes from three locations on Joint Base Elmendorf-Richardson (JBER); and (b) use the measurements to develop a predictive model of received level (RL) based on shot size, distance to the water, and environmental data. The highest sound pressure level (SPL) was 147 dB re 1 μPa root-mean-square (hereafter simplified as dB_{rms}). This RL came from both a 151 lb NEW surface shot recorded at a distance of 3150 ft (959 m) from the detonation site. A predictive model determined that underwater SPLs are not likely to exceed 150 dB_{rms} re 1 μPa from charges originating near Eagle Bay at distances greater than 2600 ft (800 m) from the detonation site, including charges up to 200 lb NEW. However, to be conservative a maximum predicted SPL of 155 dB_{rms} should be used as the highest estimate.

Introduction

Direct measurements of in-water noise from land-based explosions originating from Joint Base Elmendorf-Richardson (JBER) in Anchorage, Alaska were taken over five days in October 2012 and June 2013. This effort was conducted in accordance with two Endangered Species Act (ESA) Section 7 consultations (NMFS 2012; 2013), and in collaboration with researchers from JBER and the Army's Cold Regions Research and Engineering Lab (CRREL) and Construction and Engineering Research Lab (CERL). These measurements were necessary to develop a site-specific predictive model of in-water noise due to land-based explosions in the unique environment of the Cook Inlet. This work was done to predict the potential impact of terrestrial explosions on marine mammals including the Cook Inlet beluga whale (*Delphinapterus leucas*), which is the only beluga whale stock listed as endangered under the ESA and designated as depleted under the Marine Mammal Protection Act (16 U.S.C. 31). The Cook Inlet waters adjacent to JBER are designated as critical habitat for the Cook Inlet beluga whales (NMFS 2012; 2013).

Cook Inlet beluga whales may be present in the Knik Arm of Cook Inlet adjacent to JBER throughout the year, although they are much more likely to be present August through November, generally coincident with the coho salmon run. Beluga whales mill and forage around river mouths, including the Eagle River and Six Mile Creek, flowing into Eagle Bay and Knik Arm, respectively, from JBER land. During high tide, belugas are more likely to be present in the upper Knik Arm than in the area around Eagle Bay.

Location and Environment

The specific location of interest within the Knik Arm of the Cook Inlet is Eagle Bay, which is adjacent to JBER. Eagle Bay is contained by the cliffs to the north and Eagle River Flats, a silty estuarine area, to the southeast. A relatively deep channel, approximately 985 ft (300 m) wide at the latitude of the demo sites and 30 - 40 ft. (9.1 – 12.2 m) deep at maximum high tide, runs along the shoreline. Beyond this distance, Eagle Bay contains shallow flats that are exposed at low tide. Tidal ranges are extreme; the average tidal flux is just over 30 ft (9.1 m), from a minimum of 12 ft (3.7 m) to a maximum of about 40 ft (12.2 m). The water in Eagle Bay is very turbid due to glacial silt, with no visibility beyond a few inches.

Test detonations were performed at three locations on JBER (see Figure 1): Demo II, Demo III, and Upper Cole Point. Demo III is an Army demolitions training range located approximately 2600 ft (800 m) east of the Eagle Bay shoreline at an elevation of approximately 150 ft (45 m), and consists of a lightly sloped clearing fully surrounded by woods. Demo II is an Army demolitions training range located on a bluff approximately 650 ft (200 m) east of Eagle Bay shoreline at an elevation of approximately 90 ft (27 m). Demo II is also located in a lightly sloped clearing fully surrounded by woods. The closest shoreline features of Knik Arm to both Demo II and Demo III are the north cliffs of Eagle Bay. Eagle River, fed by runoff from Eagle Glacier, flows through the community of Eagle River and JBER before feeding into the Knik Arm of Cook Inlet at the tidal marshes of Eagle River Flats (JBER INRMP, 2006 and 2012). In winter, the Eagle River is a clear stream with very low turbidity. During spring and summer, however, there are significant levels of suspended sediment from runoff and glacial melt (Gossweiler 1984). Cole Point is a mortar firing and observation point located on an upland area south of Eagle River Flats Impact Area, overlooking Eagle River Flats. Upper Cole Point is located approximately 4.2 mile (6.7–km) southeast of the mouth of Eagle River and 1.1 mile (1.8–km) south of Eagle River at its closes point of approach. Belugas have been acoustically detected swimming up into Eagle River approximately 2.6 mile (4.2 km; the river distance) during August and September (C. Garner, personal communication).

Detailed subsurface data is limited, but in general the local geology consists of glacial sediments over bedrock (Hunter et al. 2000). The bedrock extends below the Knik Arm (approximately at a depth of low hundreds of meters). Silty sand cliffs (height approximately

100 ft [30 m]) line the north Eagle Bay shoreline, west of Demo II and Demo III. These cliffs are permeable, with observable water flow, and actively eroding, with small slides regularly entering the water. The land cover between the demo sites and the shoreline is forest.

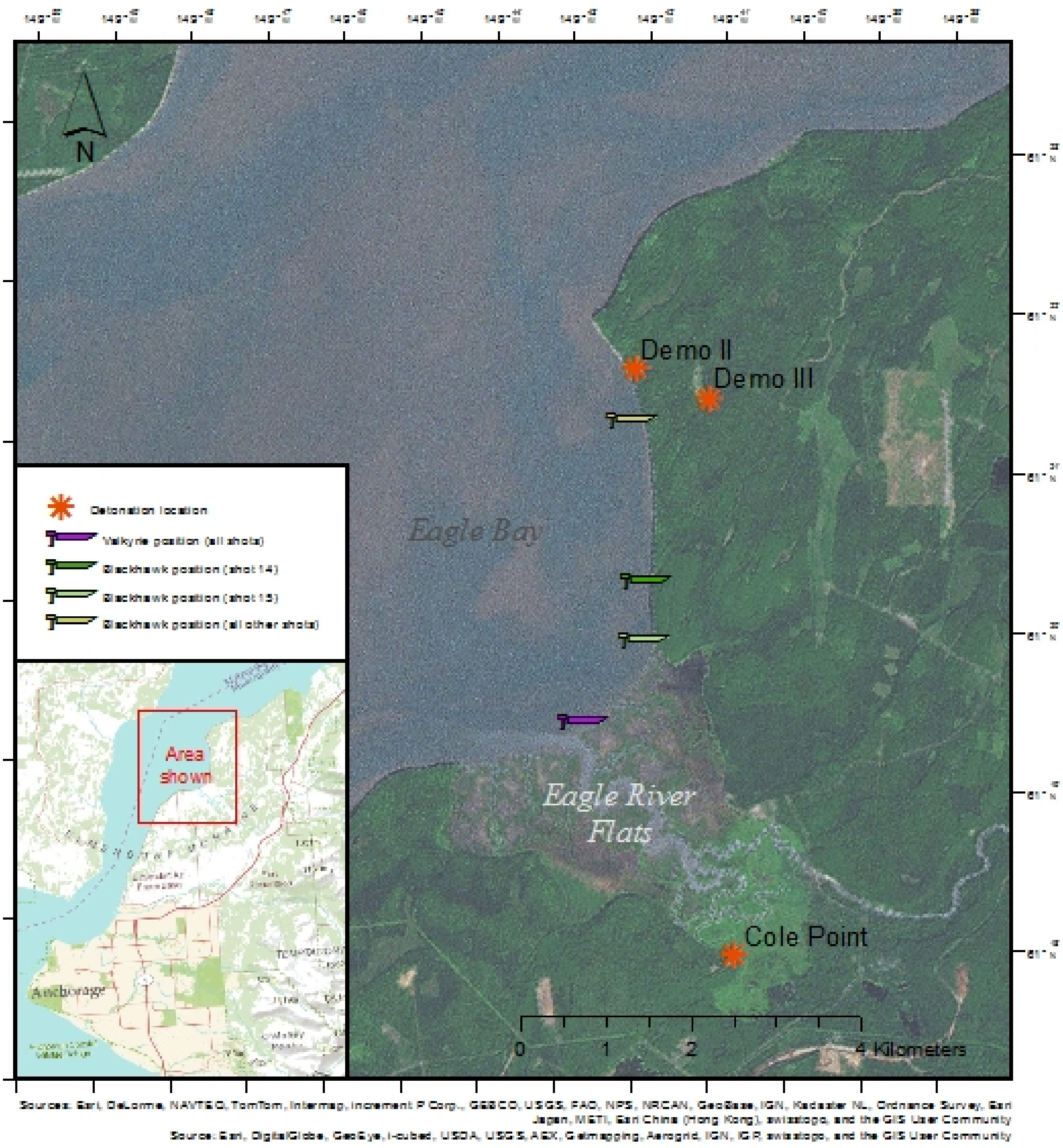

Figure 1 – Map of the Eagle Bay study area, with the locations of all detonations and recording vessels highlighted.

Methods

Field methods

On October 21 and 22, 2012, a pilot study was conducted in order to measure the underwater sound levels in Knik Arm from land-based explosions at Demo III on JBER. The underwater sound levels produced by the relatively small charge sizes used in the pilot study were not detected above background noise levels (the exception being the two buried 74 lb NEW shots and two surface clean-up shots), which prevented the development of a predictive model with a good fit to received levels. Therefore, in June 2013 a follow-on study was conducted in the same region but with larger charge sizes detonated at three different locations. Observation, recording, and analysis methods were similar to those from the pilot study, with some changes highlighted below.

Shots were detonated from three locations (Demo III, Demo II, and Cole Point) in order to compare received levels at different distances and across different propagation pathways to each recording vessel. In addition, shots of the same size were detonated both buried in a 5 ft (1.5 m) deep pit loosely covered in dirt and also on the surface. This allowed a comparison of received levels between the two detonation methods to determine if one method minimized the underwater received level more than the other. Two replicates of each charge size and condition were conducted to ensure that measurements were reliable (Table I). While having more than two replicates per condition would be ideal, the number and size of charges were limited by available C4 and the number of conditions tested.

Participants in this full study included four acousticians and two marine mammal observers from the National Marine Mammal Foundation and the Navy Marine Mammal Program in San Diego, CA, along with six expert marine mammal observers from the JBER Conservation Team, collaborating with the Army Explosive Ordnance Detachment Unit and Army Range Control, as well as members of CRREL and CERL. As in the pilot study, visual observers were stationed on land at a site south of the demolition ranges, near the mouth of Eagle River, and on a 13 ft fiberglass inflatable boat with a 20-hp outboard motor northwest of the northernmost point of Eagle Bay; observers were monitoring for belugas and other marine mammals that could approach the 1500 m mitigation zone from the north or the south (NMFS 2013). Visual observers were also stationed on each of the two recording vessels, the Valkyrie, a 26 ft cabin cruiser with twin 150-hp outboard motors, and the Blackhawk, a 20 ft open sport fishing boat with a single 115-hp outboard motor. Unlike the pilot study when the recording boats were both located in the channel, the two recording boats were stationed in different locations. This allowed the received level of the explosions to be measured from two different locations in the Knik Arm where belugas are known to transit or congregate.

Table I – Shot sequence and boat location for October and June studies.

Date	Time	Shot	Size	Location	Condition	Blackhawk		Valkyrie	
			(lb NEW)			Lat	Long	Lat	Long
10/21/12	12:22	1	5	Demo III	surface	N 61.362	W 149.713	N 61.362	W 149.719
10/21/12	13:10	2	14	Demo III	buried	N 61.362	W 149.714	N 61.362	W 149.719
10/21/12	13:22	3	14	Demo III	surface	N 61.361	W 149.713	N 61.362	W 149.719
10/21/12	13:29	4	74	Demo III	buried	N 61.362	W 149.714	N 61.362	W 149.719
10/21/12	14:14	5	cleanup[1]	Demo III	surface	N 61.362	W 149.714	N 61.362	W 149.719
10/22/12	13:04	6	5	Demo III	surface	N 61.362	W 149.714	N 61.362	W 149.718
10/22/12	13:11	7	14	Demo III	buried	N 61.362	W 149.713	N 61.362	W 149.719
10/22/12	13:16	8	14	Demo III	surface	N 61.362	W 149.713	N 61.362	W 149.719
10/22/12	13:22	9	14	Demo III	surface	N 61.362	W 149.713	N 61.362	W 149.719
10/22/12	13:40	10	74	Demo III	buried	N 61.362	W 149.713	N 61.362	W 149.719
10/22/12	13:47	11	cleanup[1]	Demo III	surface	N 61.362	W 149.713	N 61.362	W 149.719
6/14/13	10:43	1	74	Demo III	buried	N 61.360	W 149.713	N 61.329	W 149.735
6/14/13	11:46	2	151	Demo III	buried	N 61.361	W 149.713	N 61.330	W 149.734
6/14/13	11:46	3	151	Demo III	buried	N 61.361	W 149.713	N 61.329	W 149.734
6/14/13	12:32	4	40	Demo III	buried	N 61.361	W 149.713	N 61.329	W 149.734
6/15/13	12:32	5	40	Demo III	buried	N 61.361	W 149.713	N 61.329	W 149.734
6/15/13	10:41	6	151	Demo III	surface	N 61.360	W 149.715	N 61.329	W 149.736
6/15/13	10:42	7	151	Demo III	surface	N 61.361	W 149.715	N 61.329	W 149.735
6/15/13	11:18	8	74	Demo III	surface	N 61.360	W 149.715	N 61.329	W 149.734
6/15/13	11:18	9	74	Demo III	surface	N 61.360	W 149.715	N 61.330	W 149.734
6/15/13	11:59	10	40	Demo III	surface	N 61.360	W 149.715	N 61.330	W 149.733
6/15/13	11:59	11	40	Demo III	surface	N 61.360	W 149.715	N 61.330	W 149.733
6/15/13	13:08	12	14	Demo II	surface	N 61.361	W 149.715	N 61.330	W 149.733
6/15/13	13:08	13	14	Demo II	surface	N 61.361	W 149.715	N 61.330	W 149.733
6/16/13	12:46	14	74	Cole Pt	surface	N 61.344	W 149.716	N 61.330	W 149.730
6/16/13	13:08	15	74	Cole Pt	surface	N 61.337	W 149.718	N 61.330	W 149.733

[1] Clean-up shots are conducted to clear any remnant explosive materials not fully consumed in preceding shots. Exact charge sizes are unknown, but ranged between 25 – 35 lb NEW.

For shots at Demo II and Demo III, the Blackhawk was stationed in a channel about 160 – 328 ft (50 – 100 m) off the shore west of Demo III (Figure 1) adjacent to the north cliffs of Eagle Bay, while the Valkyrie was stationed about 65 – 100 ft (20 - 30 m) offshore of the mouth of the Eagle River. For the shots at Cole Point, the Blackhawk was first relocated adjacent to the southern portion of the cliffs, and then to the point where the cliffs converge with Eagle River Flats to ensure signal detection. Both vessels were in water depths of about 20 – 55 ft (6.1 –

16.8 m) at maximum high tide. Due to the extreme tidal fluctuations, all operations had to be conducted within a four-hour time window centered around maximum high tide at the transition from incoming to outgoing flow. These operations included: the launch and recovery of the boats from a boat launch about 11.5 miles (18.5 km) away at Ship Creek; a thirty-minute observation period before the firing of any shots to ensure no marine mammals were present in the area; a series of two to eight shots per day; and a final observation period of thirty minutes after the final shot to verify that no undetected marine mammals in the area were impacted.

Once each thirty-minute period of marine mammal observation was completed with no marine mammal sightings, a series of shots commenced with the following order of operation for each shot. Both recording vessels positioned themselves at their designated locations (see Figure 1 and Table I for exact positions). Under the ESA Section 7 Concurrence (NMFS 2013), a ceasefire would have been called if a beluga was observed to enter the 1500 m mitigation zone extending from Demo II and Demo III, or if a beluga was observed entering Eagle River (for the shots fired at Cole Point). The ceasefire would have remained in effect for 30 minutes or until the animal was observed leaving the mitigation zone, or exiting Eagle River in the case of Cole Point. However, no belugas were observed during any of the testing days, and therefore no cease fire was called. When both marine mammal observer platforms confirmed that there were no marine mammals present, CRREL was contacted to let them know the recording teams were ready. CRREL responded with a 10-minute shot window, at which time final confirmations were made with all teams that no marine mammals were present and that all boats were in position. At that time, both recording vessels turned their engines and depth finders off and the hydrophone arrays were deployed off the side of the boats and immediately began recording. CRREL was notified that the vessels were recording; CRREL responded with a 10-second countdown and then the shot was fired. For many of the paired replicate shots, the boats remained in position with engines off; after 60 seconds another 10-second countdown was given and the second shot was fired. After CRREL confirmed each shot was fired (as not all shots were audible from the boats), the GPS coordinates and shot time for each boat were noted. GPS coordinates were also recorded for the position of each shot at the detonation sites. The hydrophone arrays were immediately recovered and boat engines turned back on, and the process was repeated. Since the tidal current was very strong, the boats could not drift without power for extended periods of time without the concern of getting pushed on the shallow sandbar or onto the beach, so it was imperative that the recording and shot sequence happened quickly. Once all the shots and the final period of marine mammal observation were completed, the vessels returned to the boat launch and were recovered. In addition, environmental conditions were recorded by the visual observers throughout the operation. A YSI handheld temperature-salinity meter was deployed to measure water conditions near the surface, and a weather station was set up near each shot location to record atmospheric conditions (Table III; see CREL report for more details).

Underwater recordings were made using two vertical hydrophone arrays, weighted with 5-lb dive weights to maintain their vertical aspect in the current. Both arrays had two Reson TC 4032 hydrophones, deployed at 2 and 4 m depths. There was one 4032-1 hydrophone with a usable frequency range of 5 Hz to 120 kHz and a sensitivity of -170 dB re 1V/µPa (http://www.reson.com/products/hydrophones/tc-4032). The other three hydrophones were Reson 4032-2 models, with a usable frequency range of 1 Hz to 120 kHz and a flat frequency response of ±2.5 dB from 10 Hz to 80 kHz; these had the same sensitivity levels and built-in preamplifiers as the 4032 model. Each of the Reson hydrophones was connected to a Reson VP1000 preamplifier, with a high pass filter set to 1 Hz and the gain set to 20 dB on the Blackhawk and 32 dB on the Valkyrie. Both boats also recorded the airborne sounds using omnidirectional condenser microphones, with a frequency response of ±1.5 dB from 20 Hz – 20 kHz and a sensitivity of -37.1 dB re 1V/Pa at 1 kHz (beyerdynamic GmbH & Co, Heilbronn, Germany). The data from all hydrophones and microphones were digitized using an UltraLite mk3 MOTU audio device (www.motu.com) with a sampling rate of 192 kHz and a resolution of 24 bits. Phantom power (+48V) and pre-amplification was also provided to the microphones through the MOTU, with the gain varied between 10 and 15 dB on the Blackhawk and between -10 and 20 dB on the Valkyrie, depending on the shot size and location. Finally, the data were recorded to laptop computers in .wav format using the digital audio workstation software Reaper (www.reaper.fm); all three tracks were synchronously recorded as individual .wav files with time and date stamps in the filenames.

Data Processing Methods

The entire audio system (Reson 4032 hydrophones, MOTU, and VP1000 preamplifiers) was calibrated before and after the experiment using a B&K 4223 pistonphone. The calibrated functional sensitivities were determined to be between -186 and -188 dB SPL full digital scale. These values were used to determine the received levels of the shots. The received levels of each signal were quantified by selecting a window around the approximate start and end of the signal (typically 1 – 3 s). A 5 Hz high-pass filter was then applied to the time series of the windowed data to remove very low frequency noise (e.g., cable strum noise) and to normalize the low frequency floor of all four hydrophones. The sum of the cumulative sound exposure level in the window was calculated and a start point was set at 5% of the cumulative energy and an end point at 95% of the cumulative energy. The received levels in the 5-95% window were given in values of peak sound pressure level (SPL), rms SPL, and sound exposure level (SEL), calculated as 10 times the logarithm of time integral sound pressure over the duration. Ambient noise levels were measured in rms SPL using the same method; in this case, two 1-second windows were taken from before and after each of the shots in order to characterize the background noise and compare levels with those from the October pilot study. Ambient noise clips were randomly selected from periods when the hydrophones had been allowed to settle after the boats stopped moving, and clips were rejected and resampled if they included distinct noise events (e.g. banging from the boat).

M-weighting functions (analogous to C-weighting functions used for human hearing) have been developed using the estimated lower and upper frequencies of functional hearing for groups of marine mammals, termed Functional Hearing Groups (FHGs) (Southall et al. 2007). Species from four FHGs may be present within the upper Cook Inlet: mid-frequency cetaceans, high-frequency cetaceans, otariids, and phocids. M-weighting functions were applied to the recorded shot signals to determine the perceived loudness of the sound to an animal within the FHG by de-emphasizing frequencies near the bounds of the FHG's hearing range. The peak frequencies from explosive signals are well below the region of best hearing sensitivity for most marine mammals (e.g. belugas, harbor porpoises, harbor seals, sea lions).

After the October pilot study, a simple predictive model was developed by fitting a line to the SPL (in dB_{rms}) versus the log of the shot weight (in lb NEW) for shots at Demo III. Due to limited data, this model assumed that surface and ground shots would have similar received levels underwater. After the June study, when more data was available, multiple models were developed. First, the shots from Demo III recorded by the vessel in the channel were modeled based on charge size alone for both surface and buried shots. Second, a model was developed of all surface shots from all locations recorded on both vessels, using both distance between shot and receiver and charge size. Finally, the relationships between SPL and some of the environmental variables were explored, to look for additional variables that may contribute to the received levels.

Results

All 15 shots were successfully conducted over June 14-16, 2013. All five buried shots (shots 1-5) were detonated at Demo III on the first day, while all six surface shots at Demo III (shots 6-11) plus two small surface shots at Demo II (shots 12-13) were detonated on the second day. Finally, two surface shots (shots 14-15) were detonated at Cole Point on the third day. Table II gives the location, charge size, condition (buried versus surface), hydrophone depth, and highest received level for each shot. Due to a miscommunication the buried 74 lb NEW shot was not recorded on the Blackhawk, and due to the distance and the smaller charge size, neither of the 40 lb NEW shots were received on the Valkyrie. The underwater received level was strongly dependent on the size of the charge, the distance between the detonation and the receiver, and whether or not the shot was buried or on the surface. The Blackhawk, positioned in the channel just offshore of Demo II, received many of the shot signals through both ground- and air-pathways. Since all recordings were made synchronously, the time of arrival of the signal on the hydrophones could be compared with that of the in-air microphone, and the difference between them could be calculated. In addition, the shape of the signal waveform itself differed based on the pathway; the signal from the ground-path had a sharper onset, with longer reverberation, while the signal from the air-path was sinusoidal and attenuated quickly (Figure 2). The received pulses from the air- and ground-pathways were separated by about 2.3-2.4 s for the shots at Demo III, and by about 1.2-1.3 s for the shots at Demo II. In addition, the deeper 4m hydrophone on the Blackhawk had higher received levels from the ground-path of the buried shots; in fact the reverberation of the ground wave(s) masked the arrival of the air-path from all of the buried shots (Figure 3). On the other hand, the shallower 2 m hydrophone often had a higher received level from the air-path of the surface shots (Figure 2). Therefore, due to the range of possible received levels (up to four possible different levels per shot) only the highest received level for each shot from each vessel is reported here, regardless of hydrophone depth or sound path (see Table II). None of the shots received at the Valkyrie had both pathways, presumably due to the increased distance. As some of the shots were not detected on the in-air microphone it is unknown whether the signal on the hydrophone was from the air- or ground-pathway; however, they were all assumed to be from the air-pathway based on those that were also detected on the microphone.

The two loudest ground-path RLs were from the 14 lb NEW surface shot at Demo II (shot 13, 144.9 dB_{rms} at 560 m) and the 151 lb NEW buried shot at Demo III (shot 3, 145.3 dB_{rms} at 867 m), both received in the channel by the Blackhawk. The two loudest air-path RLs were from the two 151 lb NEW surface shots at Demo III (shot 6, 147.1 dB_{rms} at 959 m and shot 7, 144.4 dB_{rms} at 959 m).The highest RLs on the Valkyrie, stationed at the mouth of Eagle River Flats, were from the 151 lb NEW surface shot (shot 7, 131.8 dB_{rms} at 4215 m) at Demo III and the two 74 lb NEW shots at Cole Point (shots 14 and 15, 137.5 and 136.7 dB_{rms} at 3282 m).

However, the received levels of these signals were greatly reduced when the M-weighting functions were applied to the data. M-weighting functions were applied for each of the four FHGs that could be in the area during training events at JBER: beluga whales (mid-frequency cetaceans), harbor porpoise (high-frequency cetaceans), Steller sea lions (otariids), and harbor seals (phocids). Table III gives the weighted received levels for each group. For all of the surface shots, the M-weighted received levels were at or below background noise levels. The ground-path of the buried shot is more broadband, and so although the M-weighted received level was reduced for all FHGs, it was not as great a reduction as occurred for the narrowband, low frequency air-path from the surface shots.

Environmental conditions were radically different in June than they were in October (Table IV), with air and water temperatures about 18 - 23°C and 10°C warmer, respectively. There was also ice on the water in October, a stronger current, and a slightly higher sea state. This, in addition to heavier equipment with little self-noise and less flow noise, led to the ability to sample lower average ambient noise level underwater, with a range of 91 – 126 dB_{rms} re 1 μPa and a mean of 115 dB_{rms} re 1 μPa (Figure 4) in June, compared to a mean of 125 dB_{rms} re 1 μPa in October.

Table II – Highest received levels from each shot in dB_{rms} re 1 µPa, dB_{peak} re 1 µPa, and dB_{SEL} re 1 $\mu Pa^2 s$ for both vessels in October, 2012 and in June, 2013. (Note that only the data from the Blackhawk is shown for October, and only the highest received level from either vessel is shown for June, with the corresponding signal pathway and hydrophone depth.)

Date	Shot	Size (lb NEW)	Location	Condition	Vessel	Distance (m)	Signal Pathway	Hydrophone Depth (m)	dB (rms)	dB (peak)	SEL
10/21/12	4	74	Demo III	buried	Blackhawk	1152	ground	4	135	144	128
10/21/12	cleanup	NA	Demo III	surface	Blackhawk	1154	air	4	123	136	123
10/22/12	9	74	Demo III	buried	Blackhawk	1122	ground	4	139	151	136
10/22/12	cleanup	NA	Demo III	surface	Blackhawk	1170	air	4	115	128	117
6/14/13	1	74	Demo III	buried	Blackhawk	880	NA	NA	NA	NA	NA
6/14/13	1	74	Demo III	buried	Valkyrie	4148	air	4	110	120	107
6/14/13	2	151	Demo III	buried	Blackhawk	873	ground	4	145	154	141
6/14/13	2	151	Demo III	buried	Valkyrie	4147	air	2	110	131	110
6/14/13	3	151	Demo III	buried	Blackhawk	867	ground	4	145	156	141
6/14/13	3	151	Demo III	buried	Valkyrie	4118	air	4	110	119	111
6/14/13	4	40	Demo III	buried	Blackhawk	877	ground	4	131	142	127
6/14/13	4	40	Demo III	buried	Valkyrie	4153	NA	4	NA	NA	NA
6/14/13	5	40	Demo III	buried	Blackhawk	869	ground	4	132	141	129
6/14/13	5	40	Demo III	buried	Valkyrie	4159	NA	NA	NA	NA	NA
6/15/13	6	151	Demo III	surface	Blackhawk	959	air	2	147	153	142
6/15/13	6	151	Demo III	surface	Valkyrie	4161	air	2	130	140	129
6/15/13	7	151	Demo III	surface	Blackhawk	959	air	2	144	152	141
6/15/13	7	151	Demo III	surface	Valkyrie	4215	air	2	132	138	127
6/15/13	8	74	Demo III	surface	Blackhawk	1010	air	2	142	148	138
6/15/13	8	74	Demo III	surface	Valkyrie	4159	air	2	128	136	130
6/15/13	9	74	Demo III	surface	Blackhawk	1000	air	2	143	148	139
6/15/13	9	74	Demo III	surface	Valkyrie	4090	air	2	129	136	124
6/15/13	10	40	Demo III	surface	Blackhawk	966	air	2	138	144	134
6/15/13	10	40	Demo III	surface	Valkyrie	4103	air	2	129	136	125

Date	Shot	Size (lb NEW)	Location	Condition	Vessel	Distance (m)	Signal Pathway	Hydrophone Depth (m)	dB (rms)	dB (peak)	SEL
6/15/13	11	40	Demo III	surface	Blackhawk	953	air	2	135	144	133
6/15/13	11	40	Demo III	surface	Valkyrie	4054	air	2	130	138	125
6/15/13	12	14	Demo II	surface	Blackhawk	547	air	2	143	152	136
6/15/13	12	14	Demo II	surface	Valkyrie	4179	air	2	130	141	124
6/15/13	13	14	Demo II	surface	Blackhawk	560	ground	4	145	154	136
6/15/13	13	14	Demo II	surface	Valkyrie	4205	air	2	130	142	125
6/16/13	14	74	Cole Pt	surface	Blackhawk	4523	air	2	118	123	117
6/16/13	14	74	Cole Pt	surface	Valkyrie	3282	air	2	138	146	135
6/16/13	15	74	Cole Pt	surface	Blackhawk	3818	air	2	119	127	116
6/16/13	15	74	Cole Pt	surface	Valkyrie	3282	air	2	136	145	132

Table III – M-weighted received levels (in dB_{rms} re 1 μPa) for the shots with the highest received levels for each of the four functional hearing groups that could be present in the Knik Arm.

Shot	Vessel	Signal Pathway	Unweigted SPL	M-weighted SPL			
				Mid-Frequency Cetaceans	High-Frequency Cetaceans	Otariids	Phocids
#3 – 151 lb NEW buried	Blackhawk	ground	145	124	120	138	134
#6 – 151 lb NEW surface	Blackhawk	air	147	102	101	120	111
#6 – 151 lb NEW surface	Valkyrie	air	132	93	88	114	107
#14 – 74 lb NEW surface (Cole Pt)	Valkyrie	air	138	112	108	123	119

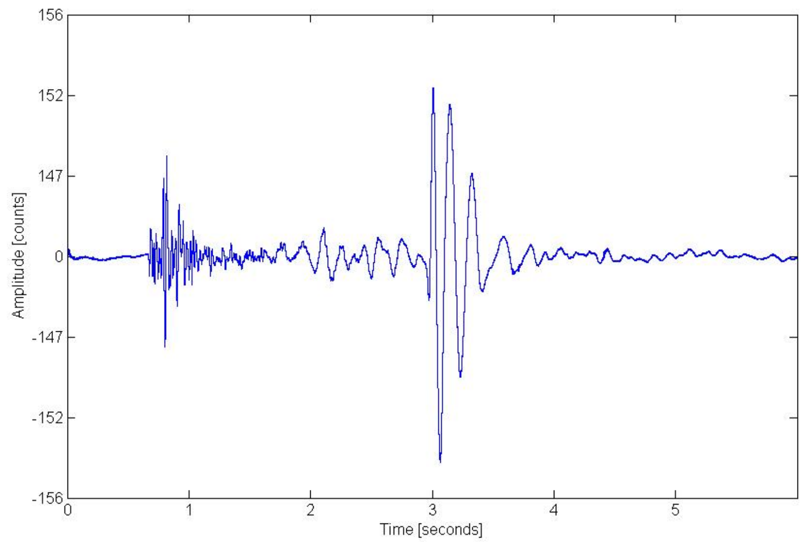

Figure 2 – Time series of the first *151 lb (NEW) surface shot* at Demo III (shot #6), with the ground (first) and air (second) received peaks. This data is from the *shallower, 2m* depth Reson 4032 deployed from the Blackhawk in the channel off Demo II/III. The y-axis is the peak amplitude of the signal in dB re 1 μPa.

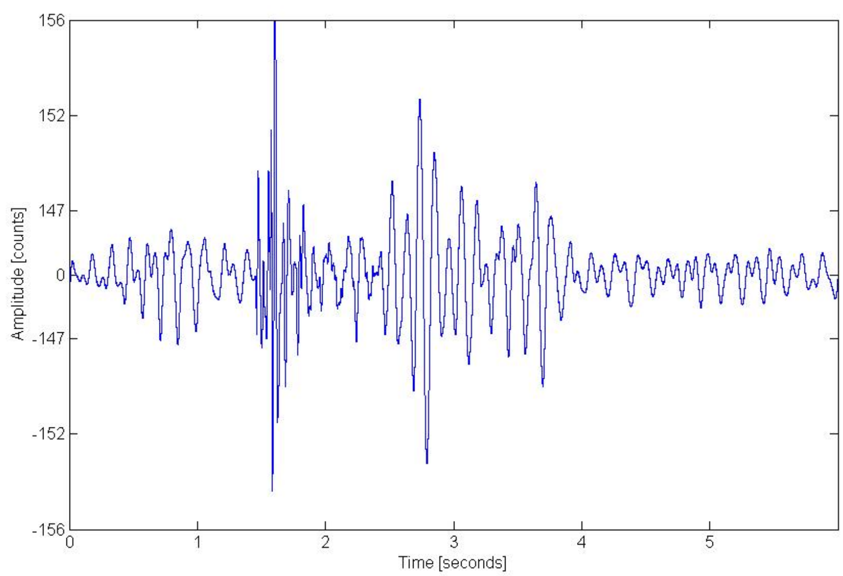

Figure 3 – Time series of the second *151 lb (NEW) buried shot* at Demo III (shot #3), with the two seismic ground wave(s) that masked the air-path. This data is from the *deeper, 4m* depth Reson 4032 deployed from the Blackhawk in the channel off Demo II/III. The y-axis is the peak amplitude of the signal in dB re 1 μPa.

Table IV – Averaged daily environmental data, taken from the JBER weather station 3.3 km northeast of Demo III (October) and from a weather station set up near each detonation site (June) by CERL. The in-water data were taken with a handheld YSI temperature-salinity meter at a depth of approximately 1 m.

Date	Air Temp (°C)	Water Temp (°C)	Salinity (ppt)	Beaufort Sea State	Relative Humidity %	Wind Speed (m/s)	Gust Speed (m/s)	Wind Direction (ø)	Solar Radiation (W/m²)
10/21/2012	0.5	2.8	7.4	1	41.8	1.8	3.7	276.0	140.4
10/22/2012	-1.5	2.7	7.5	1	51.0	1.7	3.1	263.3	147.7
6/14/2013	17.5	13.0	11.6	0.5	54.6	1.2	2.0	207.2	636.9
6/15/2013	18.2	12.8	10.6	0.3	59.8	1.5	2.3	248.1	623.0
6/16/2013	23.6	13.7	9.5	0.0	48.5	0.3	0.7	205.7	678.8

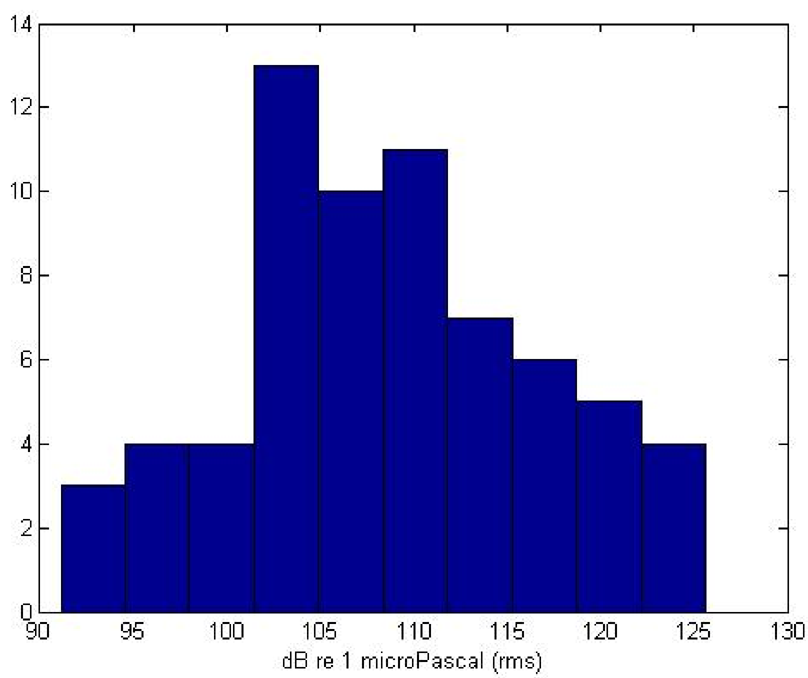

Figure 4 – Histogram of broadband, unweighted ambient noise levels in the Knik Arm in June, 2013 from 67 1-second recordings.

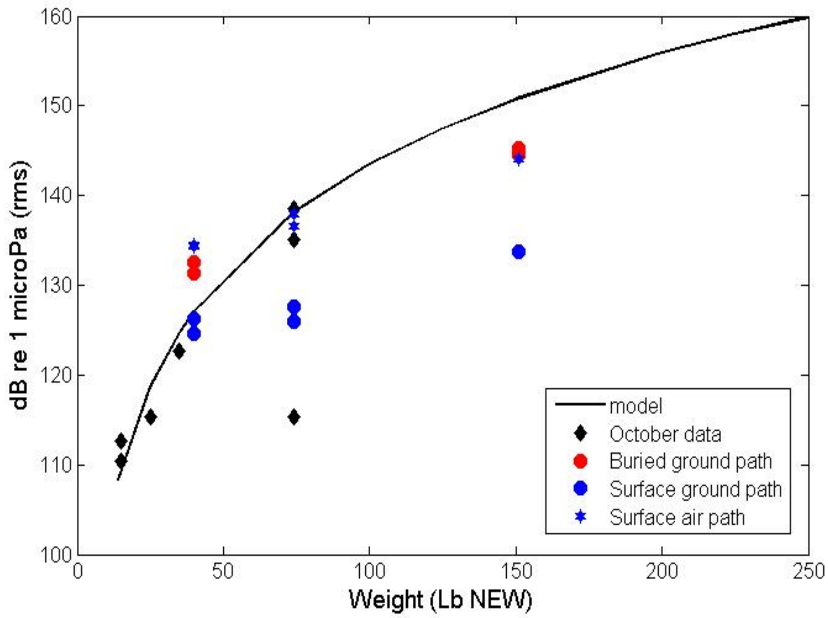

Figure 5 - A comparison of the received levels (rms) of the Demo III shots recorded in October (black diamonds) and the predictive logarithmic model used in October (black line) to the Demo III shots recorded in June at Demo III. The received levels from the buried shots (ground path) are in red circles, from the buried shots (air path) in red stars, from the surface shots (ground path) in blue circles, and from the surface shots (air path) in blue stars. Plotted data from Reson 4032 hydrophones at 4m depth, deployed from the Blackhawk in the channel off Demo II/III.

Data Models

Figure 5 shows a comparison of the received levels from October to those from the June study, along with the predictive logarithmic model line developed from the pilot study data. For this comparison only the June shots recorded on the Blackhawk on the 4m deep hydrophone were used, so as to be comparable to the results from October. The model clearly over-predicted the received levels for the larger charge sizes, particularly those detonated at the surface. However, this model was fit using only the two buried surface shots and the clean-up shots, and so was known to be limited in scope and power. Therefore, with the additional data from the June study, the data were able to be divided between buried and surface shots and modeled separately. Since the ground-path was the only one received for the buried shots for the vessel in the channel, and since all buried shots occurred at Demo III, the buried shots were modeled using only the most intense ground-path (highest RL) received on the Blackhawk hydrophones. This allowed us to model a simple linear and logarithmic fit between W, the charge size (in lb NEW), and L, the received level (in dB_{rms}) (Figure 6). The equations for the buried linear (a) and buried logarithmic (b) fits for the buried shots at Demo III are:

(a) $L = 0.1*(W) + 127.0$, $R^2 = 0.73$ [buried linear fit]

(b) $L = 9.12*\log(W) + 95.64$, $R^2 = 0.79$ [buried logarithmic fit]

Received levels of 10 dB_{rms} above and below the best fit lines were also modeled as a buffer to account for the uncertainty inherent in modeling data with only two replicates of each treatment and in a limited range of environmental conditions. 10 dB was chosen because it was the greatest difference recorded between two replicates. For direct comparison, the most intense received levels from the surface shots fired at Demo III and received at the Blackhawk in the channel were also modeled using a linear and logarithmic fit, following the same methods used for the buried shots (Figure 7). In this case, the air path only is used for the smaller charge sizes, but both the ground and air paths are used for the 151 lb NEW shot, since they produced similar SPLs. The equations for the surface linear (c) and surface logarithmic (d) fits for the surface shots at Demo III are:

(c) $L = 0.13*(W) + 133.0$, $R^2 = 0.53$ [surface linear fit]

(d) $L = 11.42*\log(W) + 88.98$, $R^2 = 0.68$ [surface logarithmic fit]

These signals largely resulted from the air path.

For both the surface and buried shots at Demo III, neither the logarithmic nor the linear models predict received levels in the channel along the Eagle Bay shoreline greater than about 145 -150 dB_{rms} for shots up to 200 lb NEW, with the 10 dB_{rms} buffer predicting levels up to 155 - 160 dB_{rms}.

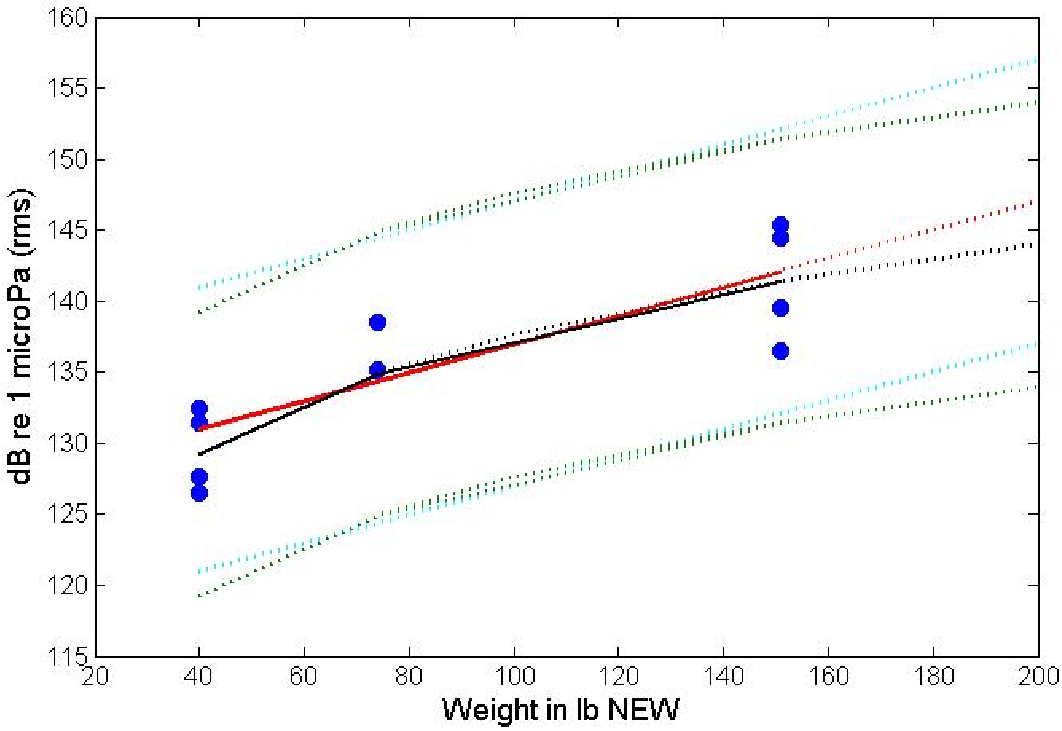

Figure 6 – The highest received levels from the *ground-path* of the *buried* shots fired at Demo III in October and June and received at the Blackhawk in the channel with a mean distance of 920 m. The solid red line is the best linear fit to the data, while the red dashed line is the predicted linear fit up to 200 lb. The lines in cyan represent the 10 dB levels above and below the modeled values. The solid black line is the best logarithmic fit to the data, while the dashed black line is the predicted logarithmic fit up to 200 lb. The green lines represent the 10 dB levels around the modeled data.

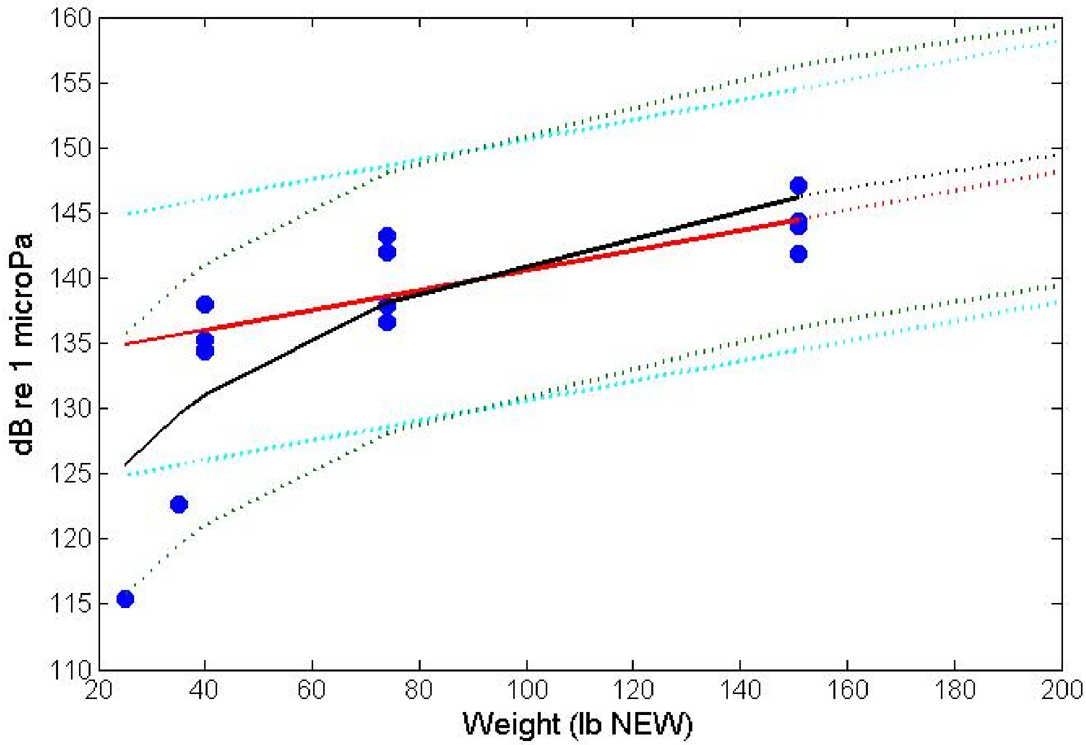

Figure 7 – The highest received levels from the *air-path* of the *surface* shots fired at Demo III in October and June, and received at the Blackhawk in the channel with a mean distance of just over 1 km. The solid red line is the best linear fit to the data, while the red dashed line is the predicted linear fit up to 200 lb. The lines in cyan represent the 10 dB levels above and below the modeled linear values. The solid black line is the best logarithmic fit to the data, while the dashed black line is the predicted logarithmic fit up to 200 lb. The green lines represent the 10 dB levels around the modeled logarithmic data.

In an unbounded body of water, sound decreases by 6 dB with a doubling of distance; this relationship can be described by the spherical spreading equation TL = 20logR, where TL is transmission loss and R is the distance. When there are boundaries (e.g. a surface and bottom), sound decreases by 3 dB with a doubling of distance; this is called cylindrical spreading and is described by TL = 10logR. The relationship between distance and a sound generated on land and received underwater is undoubtedly more complicated. Due to this relationship between distance, charge size, and received level, in order to model the data from all three locations and from both vessels a slightly more complex linear model was fit to the data. In this case, the most intense received levels from all surface shots at all locations were modeled against the log of the scaled distance (or the distance between shot and receiver (D, in m) divided by the cube root of the shot weight [$W^{1/3}$, in lb NEW]) (Figure 9). The equation for the linear fit (e) for surface shots from all locations is:

(e) $$L= -10.22*\log(D/W^{1/3}) + 196.3,\ R^2 = 0.47$$

Again, the linear model does not predict that most shots modeled at these three locations would exceed 150 dB_{rms}, and with the 10 dB_{rms} buffer none would exceed 160 dB_{rms}. It is important to note that while this linear model fit is convenient for estimation, it is not necessarily explanatory. It is a useful tool to depict the relationship between distance, charge weight, and RL, but the log(distance/$weight^{1/3}$) variable does not have meaning of its own outside of this context. Note that the two hypothetical points (200 lb NEW at 800 m and 200 lb NEW at 1600 m, in black boxes on Figure 9) represent the RLs received from the air-path for two surface shots at these weights and distances. The RL for the 800 m surface shot would be lower for the ground-path and it would be similar if it was buried (see Figure 6). It is likely the RL of the ground-path from a 200 lb surface shot at 1600 m would be less than the RL of the air-path, and may even be undetectable at that distance.

These linear and logarithmic models provide a solid framework for understanding and predicting the relationship between charge size and received level at one location (Demo III), and between charge size, distance, and received level at multiple locations. However, they are still simplistic and do not take into account other factors that may influence signal propagation and the resulting received level. There are also relationships between some of the environmental variables and the RLs, particularly for the surface shots. For example, a weak positive relationship was found between RLs and increased wind speed (R^2 = 0.1), wind direction (R^2 = 0.03), and solar radiation (in W/m^2, R^2 = 0.03), while a weak negative relationship was found between RLs and increasing air temperature (in °C, R^2 = 0.05). In contrast, there was a negative relationship between air temperature and the ground path of buried shots (R^2 = 0.03), and a positive relationship was found between Beaufort sea state and the ground path of buried shots (R^2 = 0.63) while that between sea state and surface shot RLs was much weaker (R^2 = 0.01). While most of these relationships are not as strong as that between shot weight, distance, and RL, they do indicate that there are additional factors that should be considered when estimating SPLs resulting from land-based explosions. Furthermore, although the range of environmental data collected was limited, these correlations align with what is already known about in-air sound propagation.

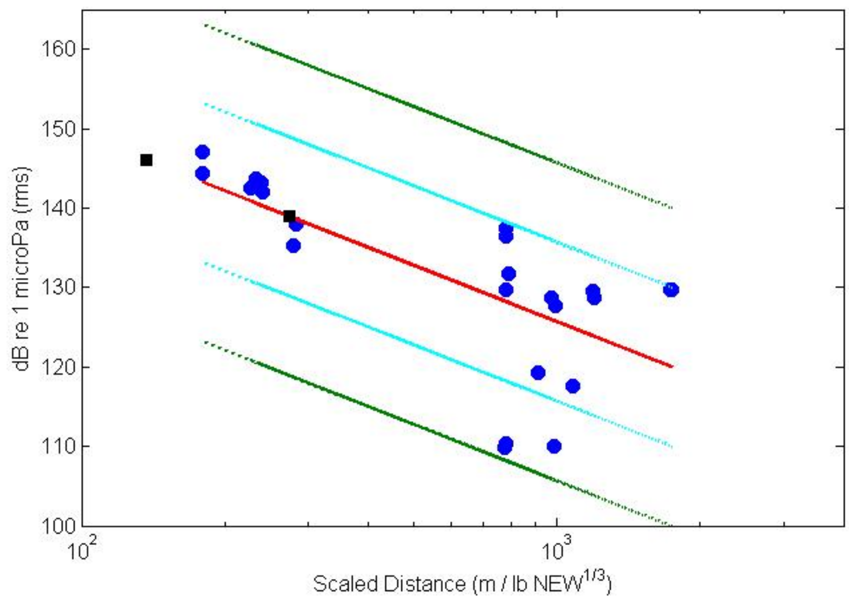

Figure 9 – The most intense received levels for all *surface* shots fired at all three locations (Demo II, Demo III, and Cole Point) and received at both vessels (Blackhawk in the channel and Valkyrie at Eagle River). The x-axis is the log of the distance between shot and receiver (in m) over the cube root of the charge weight (in lb NEW) . The red line is the best fit of the data, while the cyan lines represent the 10 dB levels above and below the modeled fit. The green lines are the 20 dB levels above and below the modeled fit. These are the 14 lb NEW shot at Demo II from the Blackhawk (145.1 dB_{rms}) and the 74 lb NEW shot at Cole Point from the Blackhawk (109.8 dB_{rms}). The black squares represent two theoretical data points for surface shots, at 200 lb NEW and 800 m, and at 200 lb and 1600 m.

Discussion

The results of the combined October and June sampling efforts have resulted in the development of multiple predictive models of underwater received levels from land-based explosions near Eagle Bay at JBER. While the results and subsequent models follow logical patterns (e.g. increased received levels occur with larger charge weights at closer distances), they are still limited and should be taken with caution. For example, there were two separate pathways (ground and air) for the signal from shots at a distance of around 1 km, and the received levels varied within the water column depending on the pathway and the placement of the shot (buried vs surface). It is unknown whether these two pathways are a result of the specific subsurface medium from Demo II and Demo III to the channel, or are merely a product of the close proximity of the Blackhawk to the detonation sites. However, the ground path may not have been received by the Valkyrie for any shots, nor was a ground path received by either vessel for the shots at Cole Point. The models were developed using only the most intense received level for each shot at each recording location in order to model the worst case scenario from this dataset. However, not all possible paradigms of charge weights, distance, location, or environmental conditions were tested, and each paradigm was only tested with two replicates. Furthermore, some of these replicates differed by up to 10 dB_{rms} re 1 μPa, such as the two 14 lb NEW surface shots (shots 12 and 13) recorded on the Blackhawk. Although 10 dB_{rms} buffers were added to the linear and logarithmic models, they are still only about 5 dB_{rms} above the most intense received levels; maximum received levels could still reach 10 dB_{rms} above these levels within the range of environmental conditions near Eagle Bay in which data was collected.

Some of the environmental variables examined were wind direction, wind speed, sea state, and solar radiation. Wind direction and speed are likely tied to the air-pathway, such that the received level underwater will be reduced if the wind is blowing in the opposite direction as the receiver from the sound source. Solar radiation is a measurement of the energy given off by the sun and the amount of cloud cover blocking it; on warm clear days sound may be refracted upwards, and therefore a decrease in received level with an increase in solar radiation may indicate that more sound was refracted away from the water with warmer temperatures. These variables had weak but positive relationships with RLs from surface shots. Air temperature had a weak negative relationship with RLs from surface shots, indicating that as air temperatures increased, the received level from surface shots decreased. An increase in sea state indicates an increase in surface waves resulting from wind, and is likely a good predictor of increased ambient noise levels underwater. While the relationship between these variables and the received level weren't strong, they were based on a limited range of observed environmental conditions. Thus, they are additional factors to take into consideration when estimating how land-based noise may propagate into the water. Under idealized environmental conditions, the resulting underwater received levels could be even higher than estimated here. With that said, the modeling results do demonstrate that it takes very large charge weights, very close distances, or idealized environmental conditions (or a combination of all three) to exceed 150 dB_{rms} re 1 μPa underwater, or 160 dB_{rms} using the conservative 10 dB buffer, from these particular sites at JBER.

Limited data exist on the behavioral responses of beluga whales to land-based explosions. The peak frequencies of these received levels are well below the region of best hearing in beluga whales, which is most sensitive between 30-50 kHz and has a threshold 40-80 dB above this level at 100 Hz (Awbrey et al. 1988; Klishin et al. 2000). As was demonstrated by applying the M-weighting functions to the most intense shots, the air-path of the surface shots would be heard by beluga whales at similar levels as background noise and so may not even be audibly detectable. The M-weighted received levels of the buried shots were 20 dB lower for beluga whales than the unweighted levels at these frequencies, indicating that this signal may also be detectable by belugas at or near background noise levels. In the future, studies in the presence of beluga whales, such as playback studies of noise with similar received levels but non-impulsive characteristics or different peak frequencies, may be useful to assess the impacts of land-based explosions.

Conclusions

These results represent the best models to date for capturing and predicting underwater noise levels from land-based explosions at various demolition sites near Eagle River Flats at JBER. The simpler linear and logarithmic models can be used to predict noise levels from Demo III, while the combined distance and weight model gives some idea of the relationship between these variables and the resulting received level at different locations. During the noise study, maximum underwater received levels were around 147 dB_{rms} re 1 μPa. However, these data are still limited, and additional information would serve to strengthen the results further. Sampling more replicates of charge sizes would provide better information on the confidence intervals that should be placed around the models; 10 dB_{rms} buffers were used here but could still over or underestimate true maximum levels. Recording at a wider variety of distances from the detonation site would also help fill in some of the gaps between the shots received within 1 km versus those received at 3 – 4 km. In particular it would be useful to know how far the ground-path of the signal propagates before attenuating, and at what distance the air path begins to dominate the received signal for buried shots.

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