

Far-field Measurements of Seismic Airgun Array Pulses in the Nova Scotia Gully Marine Protected Area

Ian H. McQuinn and Dominic Carrier

Hydroacoustic Laboratory
Maurice Lamontagne Institute
Department of Fisheries and Oceans
850, route de la Mer
Mont-Joli, Québec, Canada
G5H 3Z4

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FAR-FIELD MEASUREMENTS OF SEISMIC AIRGUN ARRAY PULSES IN THE
NOVA SCOTIA GULLY MARINE PROTECTED AREA

by

Ian H. McQuinn and Dominic Carrier¹



Hydroacoustic Laboratory
Maurice Lamontagne Institute
Department of Fisheries and Oceans
850, route de la Mer
Mont-Joli, Québec, Canada
G5H 3Z4
E-mail: mcquinni@dfo-mpo.gc.ca

¹ Physics Department, Sherbrooke University, Sherbrooke, Quebec, J1K 2R1

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ABSTRACT

Plans for conducting 3-D seismic exploration adjacent to the Sable Island Gully Marine Protected Area (MPA) prompted concerns over the potential for stress or physiological harm to the endangered northern bottlenose whale (*Hyperoodon ampullatus*) from the increased noise levels. A study of the far-field measurement of seismic pulses throughout the Gully MPA and specifically the Gully Whale Sanctuary was therefore initiated to directly measure noise levels produced by the seismic pulses and to validate the accuracy of sound propagation predictions published in the environmental assessment (EA). Our results showed that the noise levels predicted in the EA were on average underestimated by 8 dB. This finding is significant since the results of sound propagation models are used by regulators to define the safety radius for marine mammals around seismic arrays, i.e., <180 dB. The highest average sound pressure level (RMS) measured in the Gully MPA during the present study was 145 dB re 1 μ Pa at 90 m depth, 50 km from the seismic array. This sound level was measured within the Gully Whale Sanctuary while the seismic vessel was surveying the western portion of the exploration block. It was estimated that sound levels in the Whale Sanctuary would have been between approximately 153 and 157 dB when the vessel was at its closest approach to the Gully in the eastern portion of the survey block. The “worst case” sound level at the Gully MPA boundary, i.e., 0.8 km from the source, extrapolated from near-field measurements would have been approximately 178 dB, 14 dB higher than originally predicted in the EA and close to the 180 dB safety criteria. Measured sound levels were also significantly higher than the model predictions at several other stations and showed significant variability around the mean values. This demonstrates the importance of using accurate model input data, of using field validation to verify the model predictions and of the need to measure the variability around the mean sound level estimates.

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RÉSUMÉ

Des projets de relevés sismiques 3-D près de la zone de protection marine (ZPM) du Goulet de l'île de Sable ont suscité des inquiétudes quant au stress et aux impacts physiologiques que pourrait occasionner un niveau de bruit trop élevé sur la baleine à bec commune (*Hyperoodon ampullatus*), une espèce en danger de disparition. Un projet de recherche a donc été initié pour obtenir des mesures absolues par hydrophone des niveaux de bruit produits par les impulsions sismiques à travers la ZPM du Goulet et plus spécifiquement dans le sanctuaire à baleines, et pour valider la précision des prévisions du modèle de propagation présenté dans l'évaluation environnementale (ÉE). Les résultats de l'étude ont démontré que les niveaux de bruit prédits dans l'ÉE ont été en moyenne sous-estimés par environ 8 dB. Ce résultat est significatif parce que les prévisions du modèle de propagation sont utilisées directement par les gestionnaires pour définir les zones de sécurité pour les mammifères marins autour de la grappe de canons à air, i.e., <180 dB. Le niveau moyen le plus élevé de pression sonore (RMS) mesuré dans la ZPM du Goulet durant l'étude a été de 145 dB re 1 μ Pa à 90 m de profondeur, à 50 km de la grappe sismique. Ce niveau a été mesuré dans le sanctuaire à baleines du Goulet au moment où le navire sismique sondait la portion occidentale du bloc d'exploration. Il a été estimé que les niveaux sonores dans le sanctuaire à baleines aurait été entre d'environ 153 à 157 dB au moment où le navire était au point le plus rapproché du Goulet, dans le secteur est du bloc d'exploration. Le pire cas, à la frontière de la ZPM du Goulet, i.e., à 0,8 km de la source, extrapolé à partir des mesures prises à quelques km de la source, a été estimé à environ 178 dB. Ceci était 14 dB plus élevé que le niveau prédit dans l'ÉE, ce qui est près du 180 dB considéré comme étant la limite de sécurité. Les niveaux sonores mesurés étaient aussi significativement plus élevés que les prévisions du modèle à plusieurs stations d'écoute et ont montré de la variabilité autour des valeurs moyennes. L'étude a démontré l'importance de l'utilisation de données de base précises dans les modèles, de la validation sur le terrain des prévisions du modèle, et de la nécessité de mesurer la variabilité autour des valeurs moyennes estimées.

INTRODUCTION

Interest in seismic oil and gas exploration on the Scotian Shelf off Nova Scotia has been increasing in recent years, with the submission of proposals for seismic surveys in previously unexplored deep-water areas and new licenses being issued. However, the recent designation of the Sable Island Gully as a Marine Protected Area (MPA) has prompted calls for increased vigilance on the part of regulatory bodies when issuing licences near this sensitive area. The Gully MPA is an ecologically significant habitat for many marine mammals and includes a whale sanctuary (Figure 1) principally for the

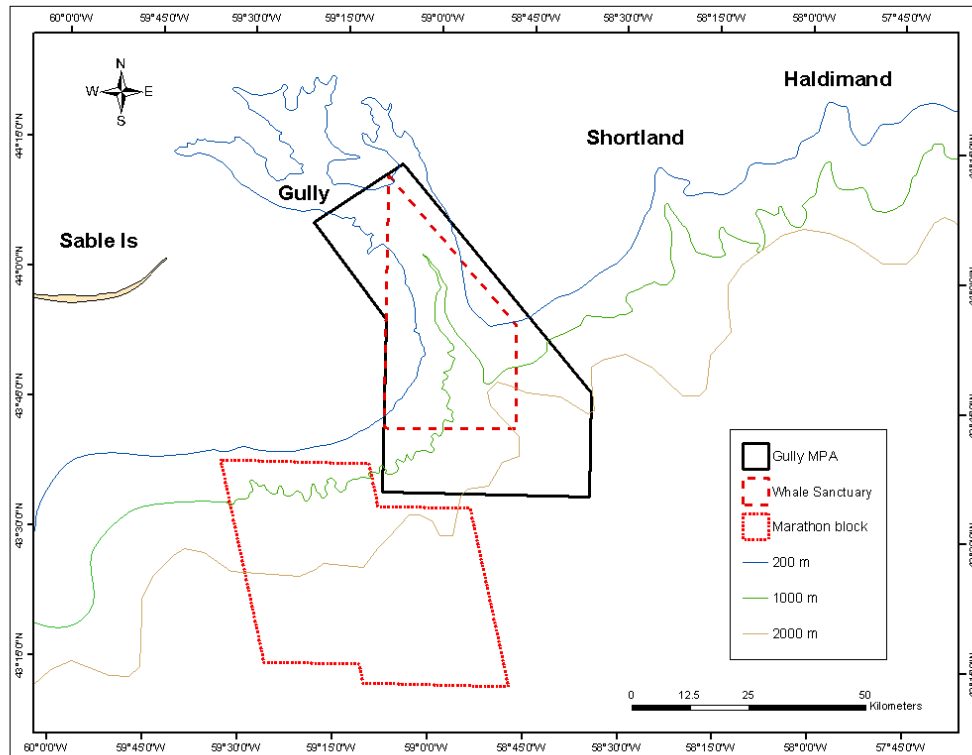


Figure 1. Location of the Marathon exploration block relative to known northern bottlenose whale habitat in the Gully MPA and the Shortland and Haldimand canyons.

northern bottlenose whale (NBW), *Hyperoodon ampullatus*, listed as an endangered species under COSEWIC (Committee on Status of Endangered Wildlife in Canada). Concerns have been raised over the potential impacts of loud noise sources such as seismic airgun arrays on the physiology and behaviour of marine mammals and in particular on special status species such as the NBW, which has its main distribution in and around the Gully MPA (Whitehead et al., 1997) and the adjacent Shortland and Haldimand marine canyons of the outer Scotian Shelf and Scotian Slope. There was therefore considerable concern over the increased noise levels produced within the Gully MPA from 3-D seismic shooting in adjacent exploration blocks leased by Marathon Canada Ltd. and EnCana Corporation and the potential for stress and physiological harm to the NBW.

Worldwide, regulatory bodies are relying on mitigation measures to lessen the impacts of seismic exploration on marine life, with particular attention to marine mammals. One of the principle mitigation measures used during seismic surveys is the definition of one or more safety zones around the array that define areas of potential physiological and behavioural impact upon marine mammals. Typically, operators may be required to cease shooting if a marine mammal is sighted within a safety zone defined as a radius around the seismic array within which the received sound pressure level (SPL) is predicted to be above a given criteria. In the case of the Marathon Canada Ltd. project, estimated sound levels were calculated for the environmental assessment (EA) from a sound propagation model for various trajectories from sources within the Marathon licence block to receive points in the near-field (i.e., within hundreds of meters of the vessel) and in the far-field, including the Gully MPA (Moulton et al., 2003). The safety radius for cetaceans was determined from these models to be 500 m for a received level of 180 dB re 1 μ Pa (RMS).

The Gully Seismic Research Program was initiated by Fisheries and Oceans Canada in partnership with the industry to study the propagation of seismic pulses into the Gully MPA from the Marathon 3D seismic survey. The present study focused on measuring seismic airgun array sound levels in the far-field throughout the Gully MPA and on validating the accuracy of far-field sound propagation model predictions from the environmental assessment (Moulton et al., 2003).

MATERIAL AND METHODS

Our study was initially planned to measure far-field (> 30 km) ambient noise before seismic shooting and sound levels when the seismic array was shooting closest to the Gully MPA. However, due to significant delays, the 90-day Marathon seismic reflection survey began several months later than scheduled. Therefore the two studies were rescheduled, one before the seismic survey (April, 2003) to measure ambient noise and to record marine mammal vocalizations and the other during seismic shooting (July, 2003) to measure the far-field seismic noise levels, ambient noise and again to record marine mammal vocalizations. However, at this time, the seismic vessel M/V *Ramform Viking* was at the western extremity of the Marathon block, some 30 km from the Gully MPA at its closest approach.

The CRV *Strait Signet* was chartered as a platform for conducting the noise recordings and for the marine mammal observations. A surface deployed calibrated hydrophone recording system called RUSTLER (Hydroacoustic Laboratory, MLI, DFO, Mont-Joli, Qc) was used for sound data collection. This system was powered from two 12-volt batteries and consisted of an omni-directional (± 1 dB) ITC6050 recording hydrophone (midband receive sensitivity: -157 dB V/ μ Pa), a Reson TC4033 reference hydrophone, a Reson TP1000 fixed gain/highpass filter (1 Hz) and a Marantz PMD670 microdrive recorder. The recording and reference hydrophones were calibrated at the Hydroacoustic Laboratory, MLI, referenced to a pistophone-calibrated B&K 8105 hydrophone. The TC4033 reference hydrophone produced a 2-sec, 10 kHz tone at 2.5-min intervals that was used to validate the system calibration coefficients after deployment. This avoids having to recalibrate the system when a component is replaced, provides a means to

ensure that the receive hydrophone is stable over time, ensures that the system amplitude corresponds to the recorded gain settings and can be used to diagnose trouble with the system or to provide warning of problems as they develop (e.g., leaks in the cable).

The frequency response of all components was measured in the laboratory and was used to normalize the sound recordings. Recordings were stored in standard PCM wav format with a bandwidth of 24,000 Hz, i.e., at a sampling rate of 48,000 samples/sec. GPS position data was collected on both vessels and referenced to the GPS time for the estimation of transmission ranges.

The survey design was a systematic grid of fixed stations covering the canyon section of the Gully MPA as well as the adjacent shelf and slopes to the southwest and northeast (Figure 2). During the April survey, RUSTLER was deployed at each station at 10, 30, 50, 70 and 90 m depth for 10 min each, depth permitting. Deployment depth was assumed from the hydrophone cable length without correction for cable angle, so any deviation from the vertical due to currents would have reduced this depth.

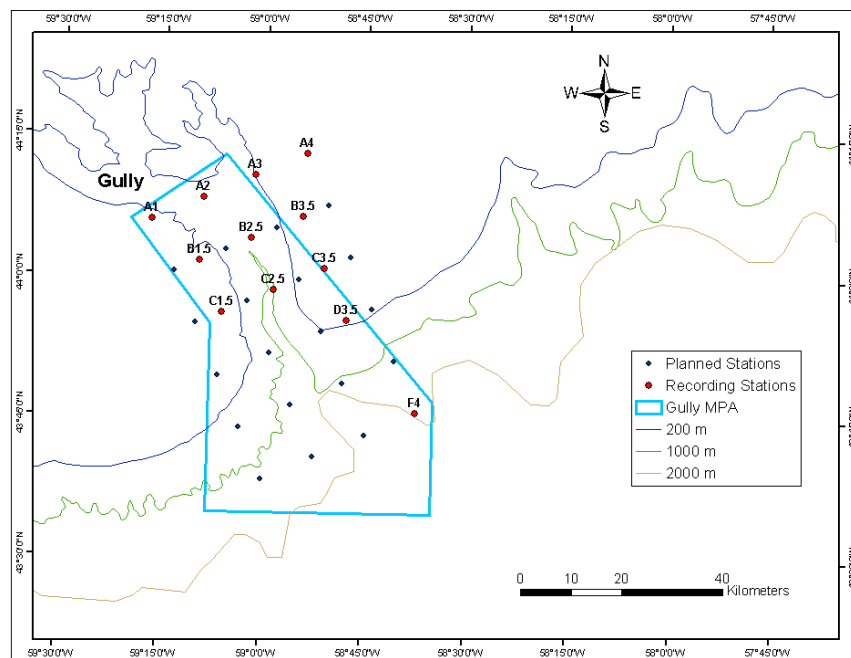


Figure 2. Sampling design for the April survey in the Gully MPA (box) showing planned and sampled recording stations.

Having RUSTLER installed on a ship allowed sampling coverage to be spread over a wide area, the monitoring of data quality and the optimal configuration of gain settings, e.g., high signal to noise ratio (SNR) while avoiding signal clipping. However, despite having the ship's engines and generators shut down during recording, a surface deployment has the disadvantage of increasing platform-related noise (PRN). In rough weather, considerable noise can be produced from the rolling of the vessel (e.g., metal-on-metal thumping noises). In April, the weather was particularly poor, and the effects on

data quality were significant, particularly at the shallower depth deployments. Therefore, for the July study, an effort was made to reduce strain on the cable and PRN. A motion compensation device was installed on the cable, which consisted of a float and rubber shock cords that helped considerably to dampen the wave-generated vertical movement of the hydrophone and to improve data quality. In addition, half-hour recordings were conducted at each station (Figure 3) at 90 m only during the second study, again depth permitting. When no seismic pulses were recorded, stations were resampled at a later date (see Table 1). Only station D3 was sampled while no seismic pulses were being emitted.

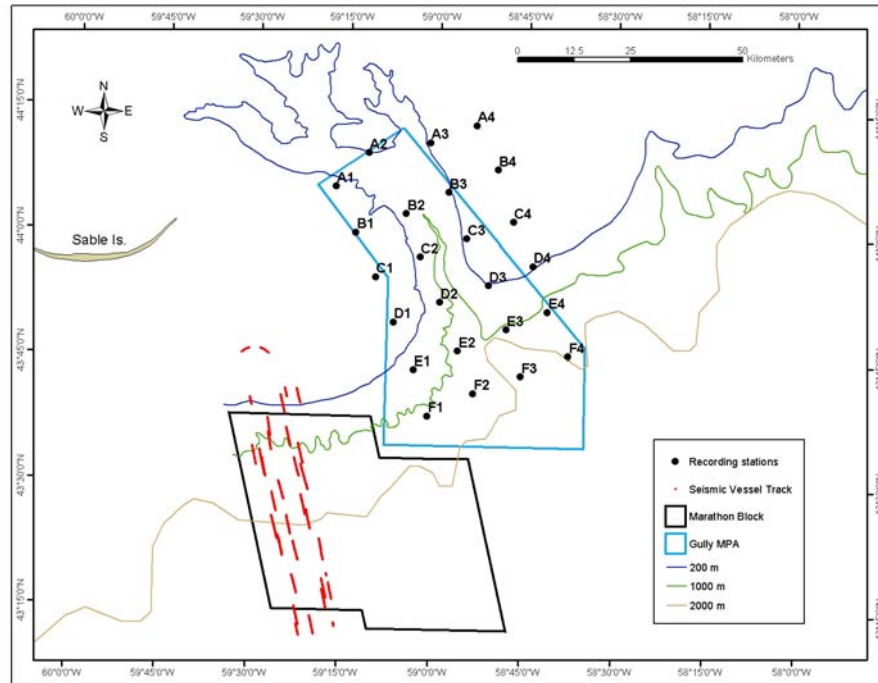


Figure 3. Recording stations and seismic vessel tracks for the July survey in the Gully MPA (light box) and showing the Marathon block (dark box).

OCEANOGRAPHIC DATA

Temperature, salinity and density profiles were collected at each station with a Sea-Bird CTD profiler to determine sound velocity profiles throughout the Gully MPA. CTD profiles were made to 550 m or to just above bottom when shallower than 550 m.

DATA ANALYSES

Sound Level: Waveform Analyses

Peak sound pressure level (peak = maximum 0-to-peak pressure level per pulse), the RMS sound pressure level (SPL_{rms} = root mean square sound pressure level over the pulse time window) and sound exposure level (SEL = sound exposure level or energy flux density over the pulse time window standardized to 1 sec) were estimated using a Matlab application developed at the Hydroacoustic Laboratory, MLI, according to the methods

described by Austin and Carr (2005). The Calibrated Ambient Noise and Sound Analysis (CANASA) software was designed to calculate calibrated receive levels from the referenced sound recordings. During analysis, the reference tone was detected and the SPL amplitudes were scaled to the theoretical receive level of the tone.

Sound recordings were analysed from each station where seismic pulses were detected, except when the airgun array was ramping up. The seismic array was assumed to be ramping up when seismic pulses were recorded but the source platform's position was determined to be outside the Marathon block.

Data files were first filtered between 10 and 1000 Hz, as all significant seismic pulse energy can be found within this band with the vast majority below 500 Hz (Moulton et al., 2003). The files were then scanned with an automatic pulse detector that determined the time window for each pulse for the estimation of the SPL_{rms} , where the cumulative energy flux density was between 5 and 95% of the total pulse (Austin and Carr, 2005). The 100% pulse time window was defined as the time at which the RMS sound pressure per consecutive 100-sample segment was below 0.1% of the cumulative energy from the beginning of the pulse (Figure 4). All detected pulses were scrutinized with a graphic

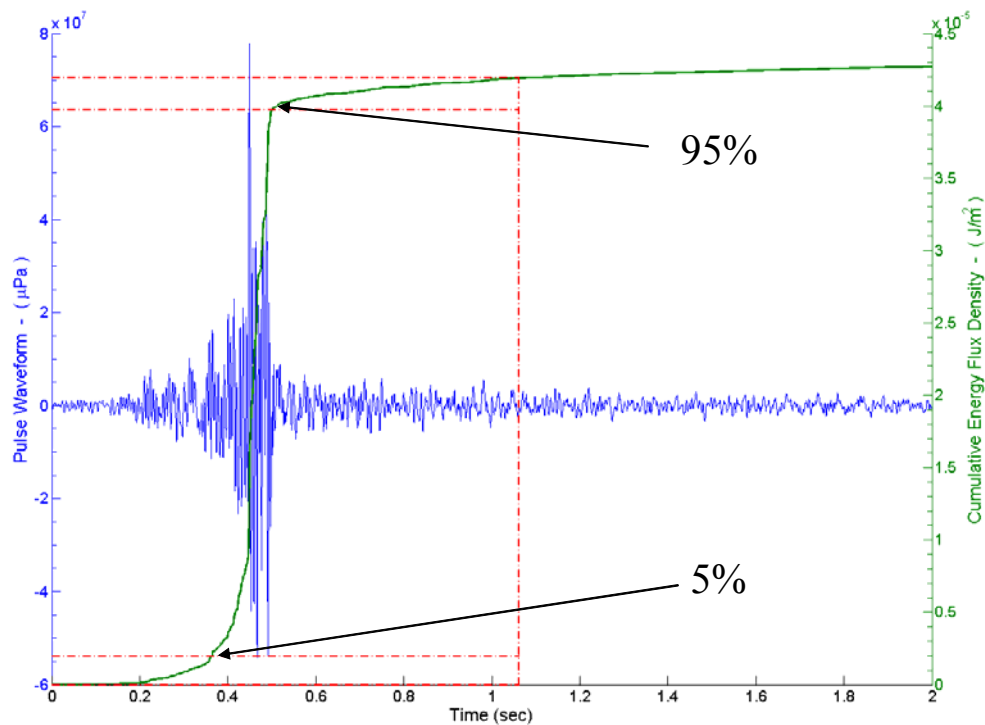


Figure 4. Determination of the pulse time window from the estimation of the cumulative energy of a seismic pulse waveform.

editor within CANASA to determine if the pulse time window was well defined. The few pulses that were poorly defined due to excessive background noise from the recording platform were eliminated. Mean values for sound pressure levels (peak, SPL_{rms} and SEL)

were estimated for each station by averaging (linear scale) over all remaining pulses ($20 < n < 166$ per station). Finally, selected stations were scrutinized to compare measured SPL results with model predictions from Moulton et al. (2003).

Sound Level: Spectral Analyses

Fast Fourier Transforms (FFT) were used to examine the frequency content of the seismic pulses at various distances from the source. Sound levels (dB re $1\mu\text{Pa}$) were measured at 1/6 octave bands (toothed whale critical band) starting at 10 Hz (central frequency) to produced 3D noise spectrograms. These sound spectra were compared to a toothed whale's audiogram to determine audibility. Although the northern bottlenose whale was the species of most concern, the only large odontocete audiogram available to us was from the beluga whale, *Delphinapterus leucas* (Erbe and Farmer, 2000). We assumed that the beluga whale audiogram would represent the upper limit of the hearing sensitivity of the northern bottlenose whale given that, in general, larger marine mammals exhibit higher sensitivity at lower frequencies. Therefore, comparison of the seismic sound levels with the beluga whale audiogram should be a conservative approximation to what a northern bottlenose whale should be able to hear at low frequencies (< 500 Hz).

Ambient Noise

For the ambient noise analyses, power spectral density (PSD) levels (dB re $1\mu\text{Pa}^2/\text{Hz}$) were estimated using FFT analysis over the recorded bandwidth and presented in 1/3 octave bands for comparison with published measurements. Files were first scrutinized with a sound file editor (CoolEdit, Syntrillium®) to identify, select and eliminate platform-related noise. Noise was considered PRN either audibly or if it appeared to be related to wave movements, such as metallic thumping. This was particularly obvious for the shallower stations.

RESULTS

SURVEY COVERAGE AND SYSTEM PERFORMANCE

Rough weather prevented sampling at 12 of the 24 planned stations during the April survey. Also, significant PRN was noted on most recordings, making the estimation of ambient noise levels difficult for those stations. Therefore, only the cleanest data were analysed. From the July survey, all stations were visited at least once and seismic pulses were recorded at all stations except D3, as the airguns were off during both visits.

PULSE CHARACTERISTICS

The highest average peak, SPL_{rms} and SEL amplitudes per station were 161 (station F1), 145 (stations E2, E3) and 144 (station F1) dB re $1\mu\text{Pa}$, respectively, during the period of our field measurements (Table 1). Pulse amplitude variability over the 0.5 h recordings was considerable both within and among stations, partially due to variable range and propagation conditions from the displacement of the source vessel, but also due to differences between the alternating arrays. The mean SPL_{rms} inter-pulse difference varied from 1 to 6 dB from station to station (Table 1). Variability of this magnitude was

Table 1. Date, location, hydrophone and bottom depth, sound speed at recording depth and estimates of peak sound pressure level, RMS sound pressure level, sound exposure level and associated statistics at each recording station.

Station	Recording Date (yyyy-mm-dd)	Latitude N (deg.dec)	Longitude W (deg.dec)	Distance to Source (km)	Hydrophone Deployment		Sound Speed (m·s ⁻¹)	No. of Seismic Pulses	Peak (dB re 1μPa)	SPL _{rms} (dB re 1μPa)	SEL (dB)	Interpulse Difference		Pulse Time Window (sec)
					Depth (m)	Bottom Depth (m)						Mean (dB)	Max. (dB)	
A1	2003-07-05	44.0967	59.2807	64.5	50	60	1463.3	47	138.2	121.3	122.6	3.9	10.4	2.6
A2	2003-07-14	44.1656	59.1917	96.1	90	230	1456.4	28	134.0	117.9	123.0	6.6	11.7	6.3
A3	2003-07-05	44.1884	59.0216	71.2	90	190	1454.9	27	131.0	117.0	126.1	3.3	9.8	7.2
A4	2003-07-05	44.2244	58.8934	90.9	45	56	1458.3	103	144.5	134.3	134.6	3.9	12.1	1.4
B1	2003-07-06	44.0057	59.2232	51.7	35	43	1463.0	150	144.1	137.6	135.4	3.2	8.4	0.6
B2	2003-07-06	44.0454	59.0843	50.9	90	300	1447.3	4	139.1	123.3	128.5	2.4	3.1	3.6
B3	2003-07-14	44.0896	58.9681	67.2	90	230	1453.6	20	142.6	131.2	129.7	3.3	8.0	0.8
B4	2003-07-05	44.1368	58.8318	101.3	75	90	1455.6	91	147.3	134.4	133.8	3.7	12.2	1.8
C1	2003-07-06	43.9176	59.1649	53.9	45	59	1456.0	66	150.7	136.1	140.6	2.7	7.4	3.7
C2	2003-07-06	43.9589	59.0428	74.7	90	292	1448.8	145	147.7	131.8	131.0	4.1	8.8	1.2
C3	2003-07-14	43.9976	58.9147	70.9	90	193	1447.9	79	145.3	134.6	136.0	3.2	10.9	2.7
C4	2003-07-14	44.0329	58.7862	89.1	90	106	1450.3	105	148.6	138.8	132.8	5.3	13.7	1.4
D1	2003-07-07	43.8273	59.1138	66.7	85	91	1449.4	95	149.9	131.5	130.9	4.5	11.4	2.1
D2	2003-07-13	43.8696	58.9862	75.7	90	550	1452.3	36	151.7	138.4	131.5	5.7	14.1	1.1
D3	2003-07-13	43.9045	58.8528		90	252	1449.3							
D4	2003-07-06	43.9447	58.7299	82.8	90	196	1448.0	82	152.0	132.6	139.5	1.7	5.5	5.2
E1	2003-07-07	43.7341	59.0547	50.7	90	309	1446.0	159	154.7	133.6	138.3	3.3	7.4	3.1
E2	2003-07-07	43.7727	58.9339	50.9	90	1300	1447.5	104	155.9	145.1	137.6	4.3	14.6	0.3
E3	2003-07-13	43.8171	58.8014	58.9	90	1100	1447.0	156	156.5	145.1	136.9	3.3	13.3	0.2
E4	2003-07-08	43.8535	58.6877	79.6	90	1220	1447.8	154	153.7	139.5	135.6	2.7	9.2	1.7
F1	2003-07-08	43.6420	59.0143	30.8	90	1250	1473.4	161	160.5	140.2	143.7	1.0	2.5	2.2
F2	2003-07-13	43.6893	58.8891	50.2	90	1300	1462.4	150	150.8	132.9	138.1	1.8	10.5	3.9
F3	2003-07-08	43.7247	58.7593	60.3	90	2500	1452.5	74	155.2	139.1	138.9	1.3	4.7	1.1
F4	2003-07-08	43.7655	58.6283	72.1	90	2000	1448.0	163	153.1	136.8	134.6	4.0	14.8	1.5
Min				30.8				4	131.0	117.0	122.6	1.0	2.5	0.2
Mean				67.9				96	152.2	137.7	136.3	3.4	9.8	2.4
Max				101.3				163	160.5	145.1	143.7	6.6	14.8	7.2

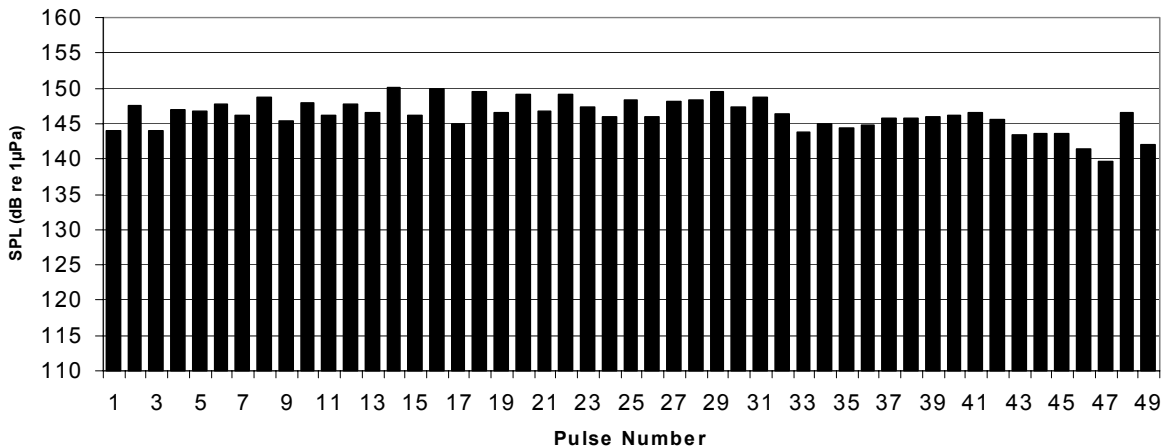


Figure 5. RMS sound pressure level per pulse at station E3 in the Gully MPA.

also seen in data presented in Austin and Carr (2005). A strong pulse was often followed by a weaker pulse (Figure 5), suggesting a regular difference between the dual arrays, and possibly related to different shot depths.

SEL and SPL_{rms} were on average quite similar in amplitude and about 15 dB less than peak levels (Table 1). The SPL_{rms} estimates were more variable than the peak and SEL

estimates (Figure 6). The increased variability in the SPL_{rms} shows the importance of the determination of the pulse time window. In general, with a decrease in multi-path echoes, e.g. fewer bottom and surface reflected echoes, the pulses were sharper and the demarcation with the ambient noise was clearer. In these cases, the beginning and end of the pulses were easier to detect, the pulse time windows were generally shorter (< 1 sec) and the SPL_{rms} was significantly higher than the SEL (Table 1). However, because the SEL is the cumulative energy, the metric was less affected by variations in pulse

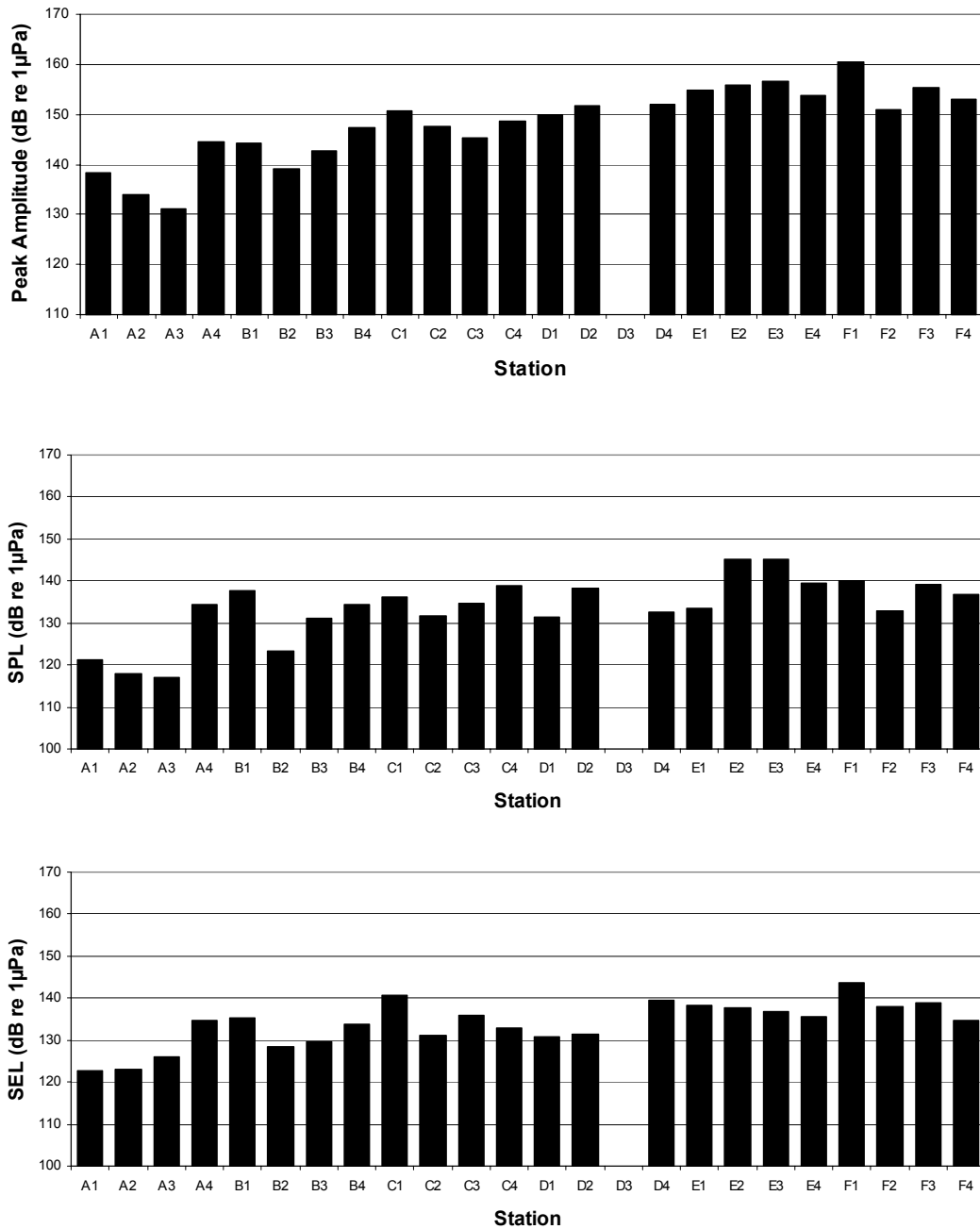


Figure 6. Peak sound pressure level, RMS sound pressure level and sound exposure level at each recording station.

windows detection, since the tail ends of the pulses contained relatively little energy, resulting in higher measurement stability.

PROPAGATION

General patterns of seismic noise propagation from the Marathon block into the Gully MPA can be observed from the spatial distribution of the mean peak, SPL_{rms} and SEL estimates (Figures 7-9). Given that the receive levels were not measured from a single source position, detailed conclusions pertaining to propagation patterns cannot be made directly from these figures. However, it is clear from Figure 7 that the peak levels decreased more consistently toward the north end of the Gully than for the SPL_{rms} (Figure 8) and the SEL (Figure 9) estimates. These figures also reveal a shadowing effect in the northwestern corner, where sound levels were reduced sharply at stations behind the Sable Island Bank. This shadowing is obvious when the estimates are plotted in relation to the distance from the source (Figure 10). All three metrics declined with distance, although again the SPL_{rms} was more variable. Note the stations in the shadow of the Sable Island Bank had lower-than-expected sound levels. The far-field sound levels from Austin and Carr (2005) were within the range of the present study, although lower than the mean amplitude given the distance from the source. Interestingly, this station was also partially shadowed by the Sable Island Bank, which could explain the below-average values.

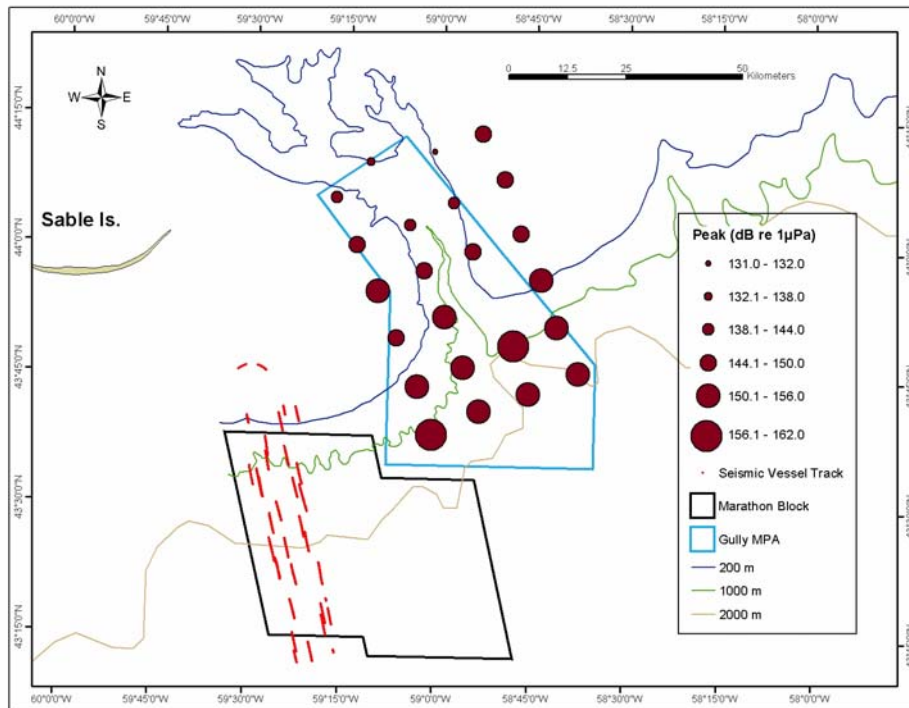


Figure 7. Peak sound pressure level and seismic vessel track for the July survey in the Gully MPA.

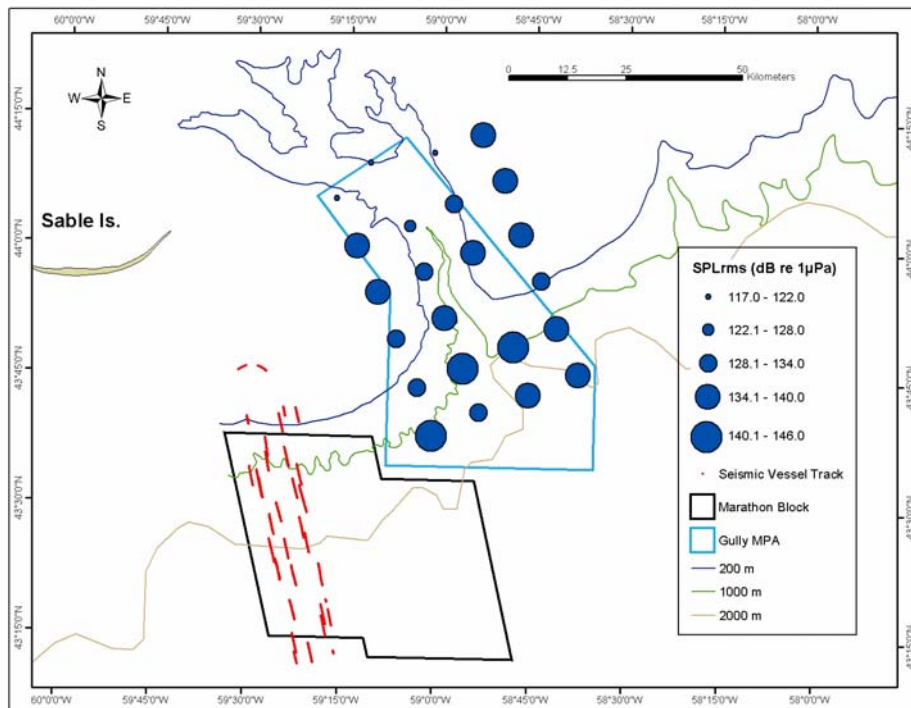


Figure 8. RMS sound pressure level and seismic vessel track for the July survey in the Gully MPA.

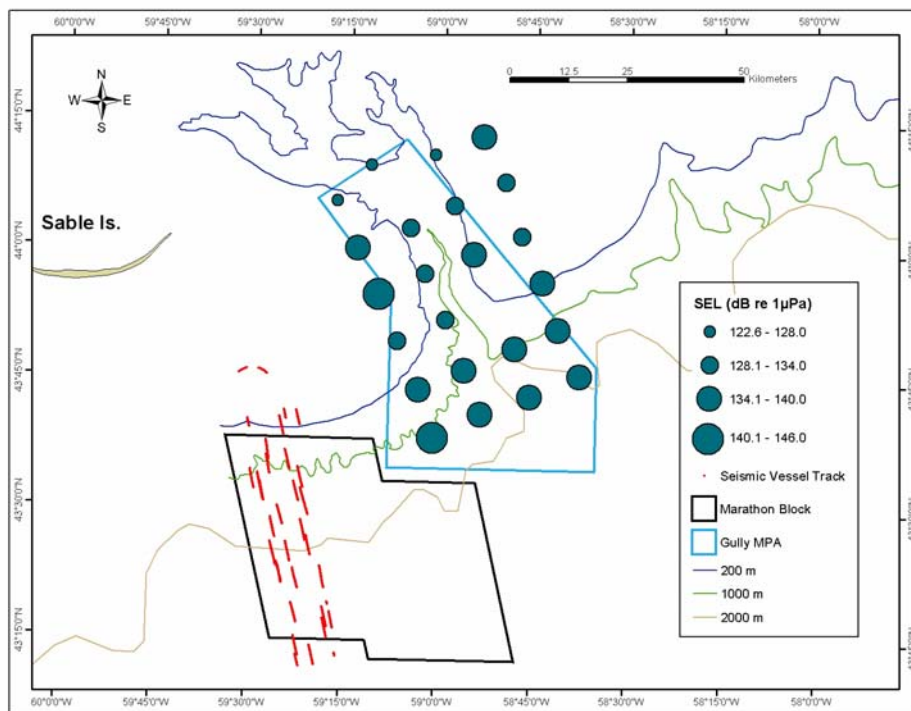


Figure 9. Sound exposure level and seismic vessel track for the July survey in the Gully MPA.

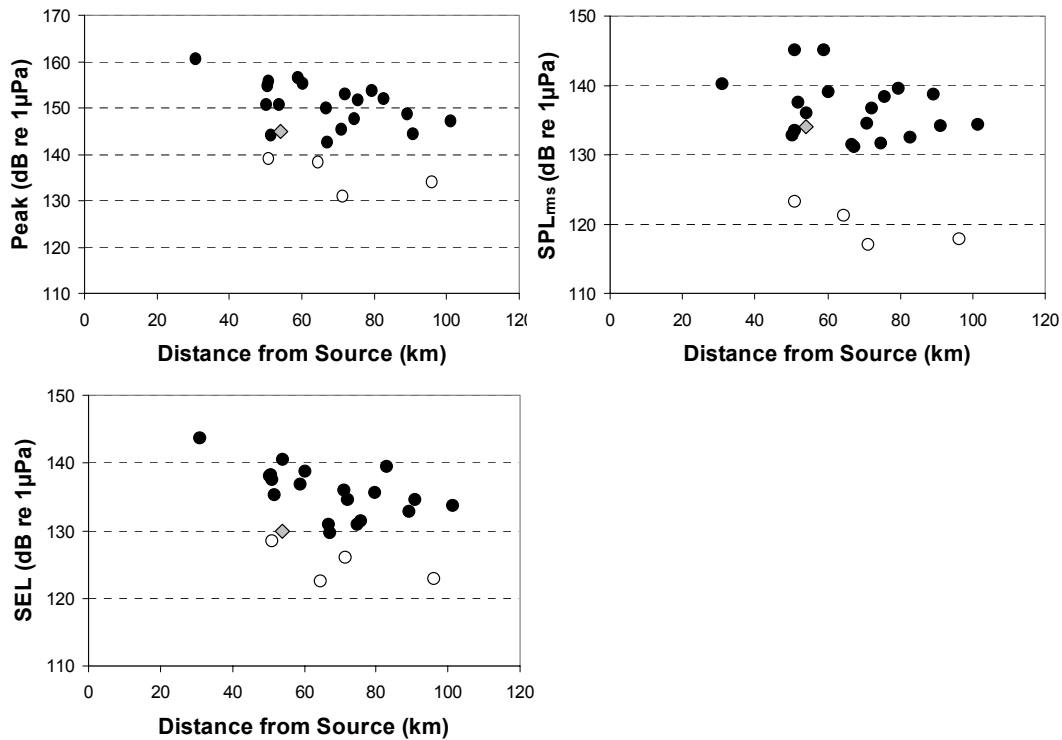


Figure 10. Far-field measurements of peak and RMS sound pressure levels and sound exposure level of seismic pulses from the present study (circles) and Austin and Carr (2004) (grey diamond) in relation to distance from the source array. Open circles are from stations in the shadow of Sable Island Bank.

PREDICTIONS FROM MOULTON ET AL. (2003)

One of the objectives of this study was to validate the accuracy of sound propagation model predictions using far-field measurements. Moulton et al. (2003) used a range-dependent acoustic model (RAM) to estimate frequency-specific 2-D transmission losses along selected tracks between the Marathon block and the Gully MPA. Although the sound propagation modelling resulted in a detailed characterization of the predicted sound field, only a few of these predictions pertained to the far field. Moreover, comparisons between the field measurements and the RAM predictions could not be made directly, principally because the source vessel and recording vessels were not positioned along the modelled tracks (Moulton et al., 2003; their Fig. 5.5) due to changes in the survey scheduling. In addition, several parameters changed between the production of the environmental assessment model results and the field work. One significant change was the seismic sound source, from a 4450 in³ to a 3090 in³ dual airgun array (Austin and Carr, 2005), resulting in the actual source levels being approximately 3 dB higher (254 versus 251 dB re 1 μPa RMS). Other factors that differed were the time of the year (July versus June) and therefore the water mass structure and assumed sound velocity profile and the depth of recording versus the depth of predictions (90 m versus 50 m), although both depths were within the subsurface sound channel.

Despite these caveats, comparisons were made between predicted and measured sound levels (Table 2) between tracks and stations that were at similar distances from the seismic source to identify if there were significant deviations from predicted levels. For these comparisons, we used the same sound level calculation as Moulton et al. (2003; their Table 7.3), i.e., the sound exposure level + 10 dB. This was necessary because the output of the transmission loss model does not provide an estimate of the pulse time window, and therefore SPL_{rms} could not be calculated directly.

Table 2. Comparison between sound propagation model predictions at various distances (identified by the track ID) in May and June (50 m) and field measurements (identified by station no.) at various stations in July (90 m).

Track Prediction	Range (km)	Predicted SEL+10 (dB)	Recording Station	Range (km)	Measured SEL+10 (dB)	Diff. (dB)
Track C (Jun)	50.0	145.3	E1	49.5	148.3	3.0
Track C (Jun)	50.0	145.3	E2	50.2	147.6	2.3
Track C (Jun)	60.0	136.6	E3	58.3	146.9	10.3
Track C (Jun)	70.0	135.0	E4	78.9	145.6	10.6
Track A (Aug)	30.0	138.7	F1	30.5	153.7	15.0
Track B (Aug)	30.0	134.5	F1	30.5	153.7	19.2
Track C (Jun)	30.0	143.4	F1	30.5	153.7	10.3
Track C (Jun)	60.0	136.6	F3	60.3	148.9	12.3
Track C (Jun)	70.0	135.0	F4	71.9	144.6	9.6

Prediction 1:

“[The strong surface] sound channel weakens after February but generally persists until late May.” (Moulton et al., 2003; p. 105)

Moulton et al. (2003) gave several transmission loss estimates for Track C, notably for May and June, when presumably water mass structure would have differed significantly. The principle difference between the spring and summer water mass structure was assumed to be the weakening of the surface sound channel, which they considered to be the major propagation feature in this region. This produced a significant decrease in the modelled receive level between May and June at 50 m (Moulton et al., 2003; their Table 7.3).

Our sampling grid of CTD profiles (Figure 3) allowed us to estimate and interpolate temperature and sound velocity along vertical slices on the major axes of the grid (Figure 11). From these data, we can see a strong subsurface sound channel that extended to the Gully area produced by a cold intermediate layer (CIL) trapped between the warm-surface and deep-bottom layers. These data also clearly show a gradient between the off-shelf area, where the seismic shooting was taking place, and the Gully/shelf area, where the CIL was a dominant feature (Figure 12). This sound channel was not predicted by Moulton et al. (2003), as only limited oceanographic data were presumably available for

this area at the time of the model runs. Therefore, using sound velocity profiles from the offshore as input into the RAM for predicting transmission losses into the Gully MPA could significantly bias predicted transmission losses.

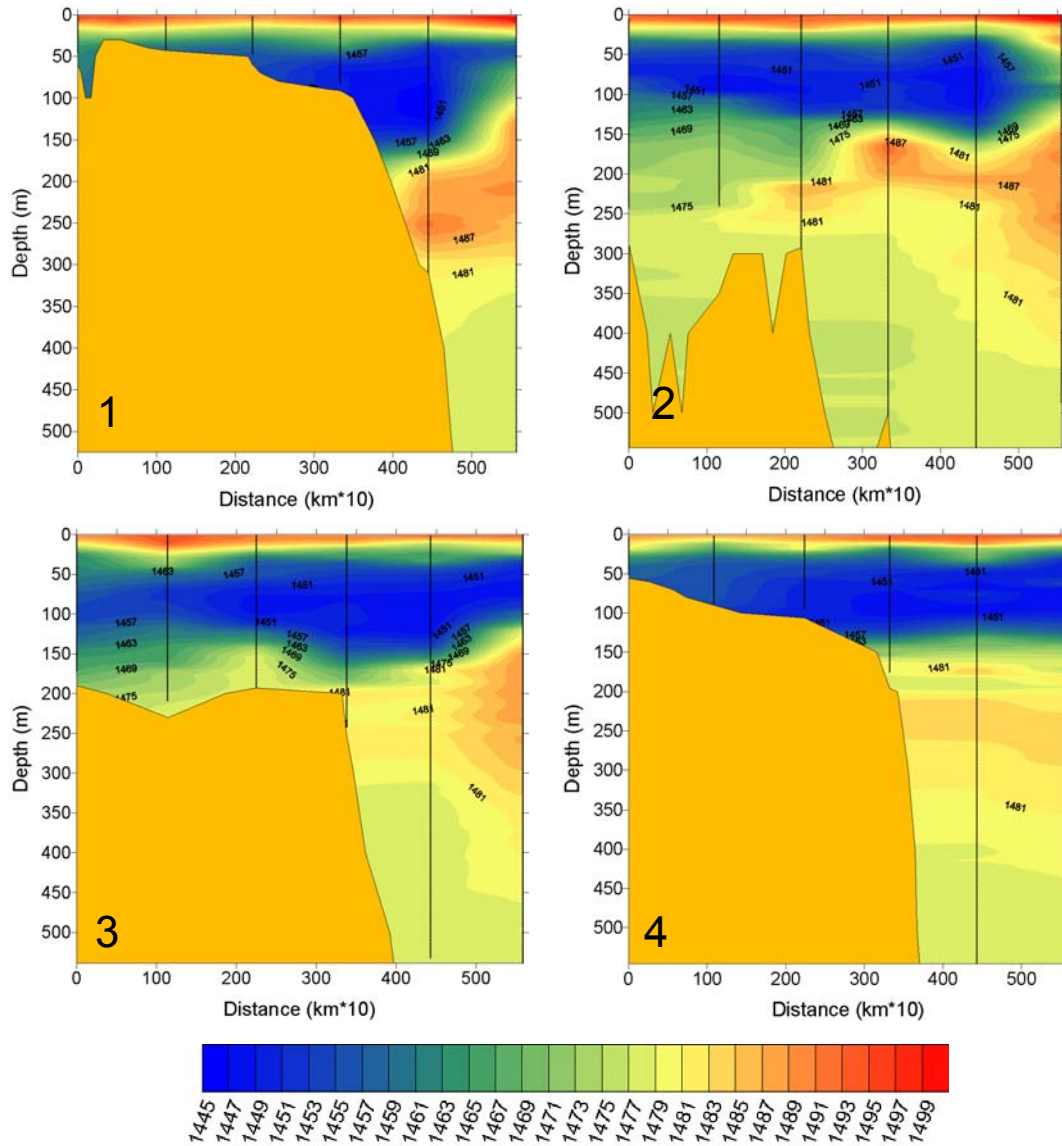


Figure 11. Interpolated sound velocity ($\text{m}\cdot\text{s}^{-1}$) along transect lines (1) A1-F1, (2) A2-F2, (3) A3-F3 and (4) A4-F4 (see Figure 3) within the Gully MPA. Black lines indicate profile positions.

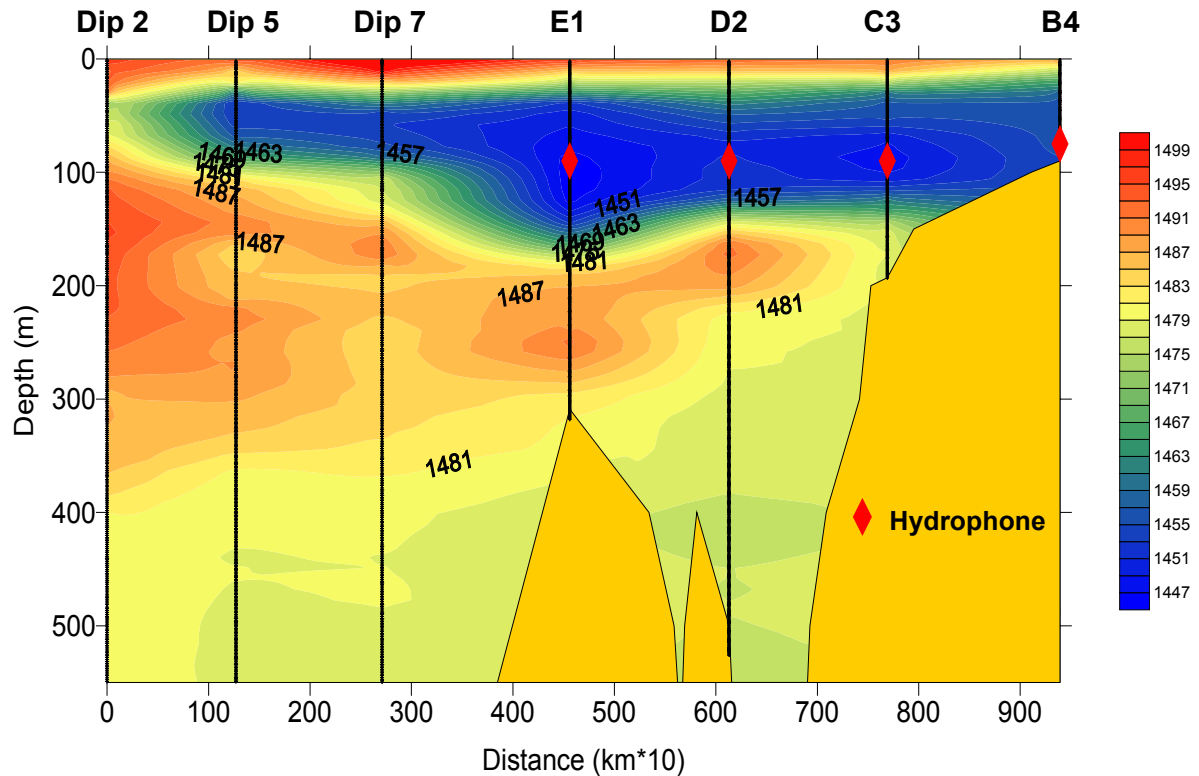


Figure 12. Interpolated sound velocity ($\text{m}\cdot\text{s}^{-1}$) from the Marathon block (Dip 2 to Dip 5) through the Gully MPA (E1 to B4) relative to the hydrophone recording depth.

Our sound level measurements recorded in July were higher than those predicted for June for similar distances (Table 2), while according to Moulton et al. (2003), they should have been considerably lower. However, our measurements were made at approximately 90 m, in the middle of the strong subsurface sound channel, which may explain part of the discrepancy.

Prediction 2:

“Sound pressure levels (rms) for airgun events reach ambient levels at ranges greater than 100 km.” (Moulton et al., 2003; p. 105)

Ambient noise levels were measured in both April and July at several stations (Figure 13). In April, no seismic shooting was ongoing, so noise levels should have been relatively typical. However, this being our first experience in collecting these data in the open ocean, there was often considerable platform-related noise on the recordings, especially at the shallower deployment depths (< 50 m). Therefore only the deep deployment (90 m) data were analysed. Also, despite our efforts to edit the data, many of these files were contaminated with PRN, mostly in the lower frequencies (< 40 Hz).

In July, with the addition of a motion compensation system on the cable and the hydrophone deployment at 90 m only, PRN was much reduced in the lower frequencies

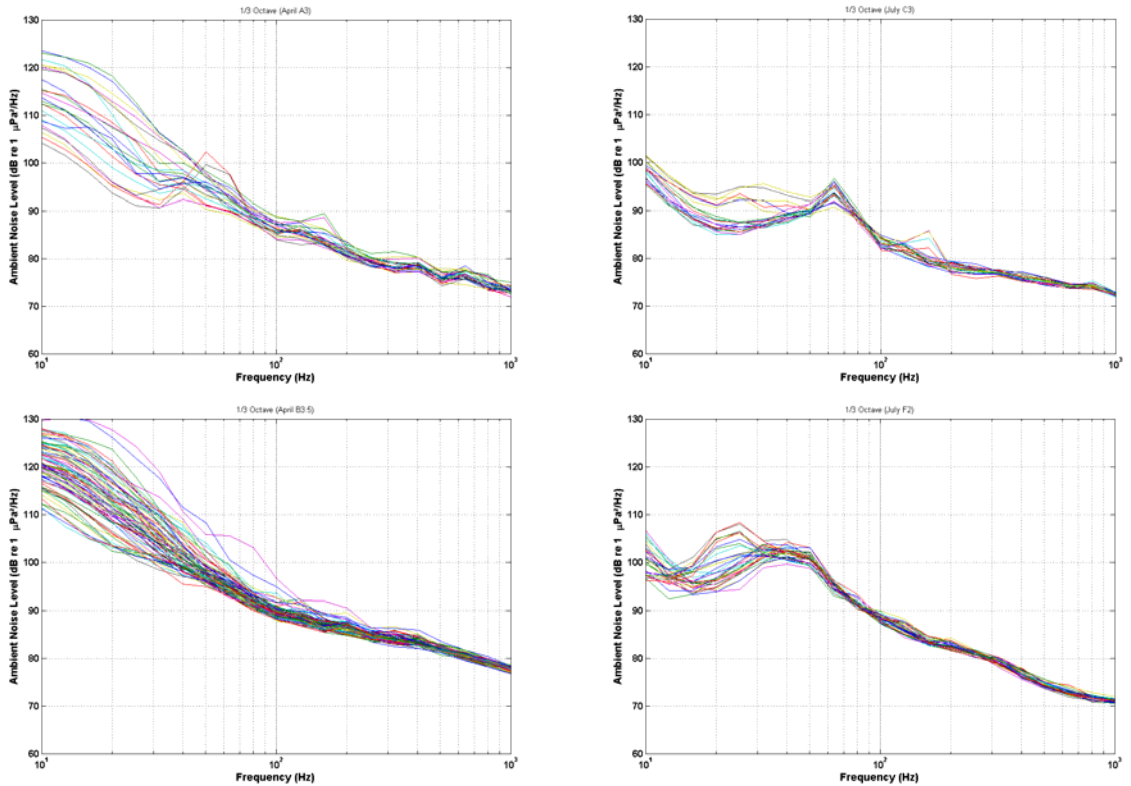


Figure 13. Average ambient noise levels (1/3 octave bands) at 2 stations in April (A3, B2.5) and 2 stations in July (C3 and F2) at 90-m depth in the Gully MPA. Note that April data below 40 Hz is contaminated with platform-related noise.

(Figure 13). Spectral densities of ambient noise in July were comparable to the levels assumed by Moulton et al. (2003) for the Gully (Desharnais and Collison, 2001). Therefore, if prediction 2 had been true, seismic pulses would not have been detectable from our recordings past 100 km. However, at station B4 (i.e., 104 km from the source), mean seismic pulse amplitudes were measured to be 134 dB re 1 μ Pa (RMS), at least 24 dB above ambient noise in high wind conditions. Not only were these pulses detectable, they would have been audible in the 250 – 630 Hz band to beluga whales and presumably to NBW at this distance (Figure 14). Although ambient noise varies over time and space, clearly there are situations in the Gully MPA where propagation conditions allowed seismic noise to be detectable by instrumentation and audible by mid-sized odontocetes over 100 km from the source. The fact that our measurements were made in July rather than June as for the model predictions should not be a factor in this difference, since according to Moulton et al. (2003), propagation efficiency should have decreased over the summer.

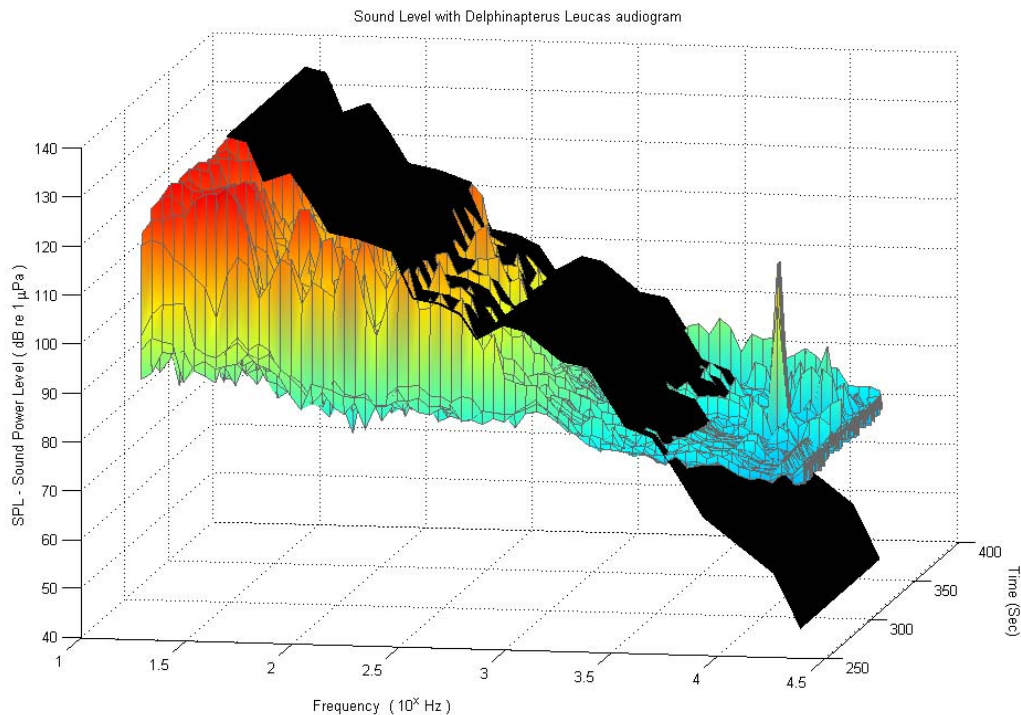


Figure 14. Sound pressure level at station B4 (1/6 octave bands) in the Gully MPA with an audiogram for a beluga whale (*Delphinapterus leucas*) superimposed (black surface). SPL above the audiogram are audible to a beluga whale (see text).

Prediction 3:

“The worst case sound level at the MPA boundary [at 0.8 km from the source] is 164.5 dB at 50 m depth in May.” (Moulton et al., 2003; p. 105)

No field measurements were taken at the location of the “worst case” identified by Moulton et al. (2003), therefore a direct comparison between measurements and predictions was not possible. Table 2 shows that, in general, the measured receive levels in July were greater on average than the model predictions for June by 8.3 dB. This suggests that the worst case sound level would have been underestimated as well. In support, the model predicted that the sound level at 50 m depth at the boundary of the Gully Whale Sanctuary would be 145.6 dB at the closest approach of 15 km (Moulton et al., 2003; their Table 7.5; Track A; Aug), whereas we measured the sound level at 90 m depth to be 147.6 within the Whale Sanctuary at a range of 51 km in July. By interpolation, the worst case sound level at the Gully Whale Sanctuary boundary would therefore be between 152.9 and 157.6 dB, depending upon whether one assumed spherical or cylindrical spreading, respectively. The environmental assessment thus underestimated the receive levels at the Gully Whale Sanctuary boundary by 7 to 12 dB. Moreover, from near-field measurements in Austin and Carr (2005), we can extrapolate the sound pressure level at 0.8 km from the source, i.e., the worst case sound level at the MPA boundary, to be approximately 178 dB, again 14 dB higher than predicted in Moulton et al. (2003) and close to the 180 dB safety criteria.

The field measurements in Table 2 represent approximations of RMS sound pressure levels, averaged over many pulses. There was nonetheless significant variability around these average values (Table 1; Figure 5). Some of this variability was from pulse to pulse, and some was over the period of the recording. Therefore, not only were average measured sound levels greater than estimated levels, individual pulses were several dB higher than these averages.

Deviations in pulse amplitude over the time of the recordings should not strictly have been due to the effects of distance since the range of distances between source and reception for a given station was 0 – 5% of the total distance due to the displacement of the source vessel. The maximum SPL was often 5 dB above the mean and on occasion as much as 9 dB higher. Therefore, it is not necessarily true that the average sound level predicted by the RAM at the closest point to the Gully MPA can be interpreted as the “worst case sound level”. Individual pulses can be significantly higher than the average.

DISCUSSION

The systematic sampling grid allowed us to produce an overall picture of the noise field within the Gully MPA, both ambient and that generated by airgun array pulses from a nearby 3-D seismic survey. The rescheduling of the survey did not allow us to take field measurements from positions identical to the published RAM predictions, nor at the closest point of approach to the Gully MPA; however, several recordings were made at similar distances from the source as those that were modelled.

Our results showed that the predictions from Moulton et al. (2003) were on average underestimated by 8 dB. This finding is significant since the results of sound propagation models are used by regulators to define the safety radius for marine mammals around seismic arrays. The field validation conducted during this and other studies as part of the Gully Seismic Research Program provided the means to monitor the sound levels and to observe that these sound levels were higher than expected. In fact, the near-field measurements reported in Austin and Carr (2005) were used to expand the safety radius from 500 to 700 m during operations.

Transmission loss models are important tools for indicating expected sound propagation patterns from a sound source such as a seismic array. However, these models are highly dependent on the accuracy and detail of the assumptions and environmental parameters put into them, including bathymetric, topographic, geoacoustic and oceanographic information (McCammon et al., 2005). For example, Moulton et al. (2003) assumed that propagation efficiency would degrade over the summer with the disappearance of the surface sound channel, while measurements taken by us and Austin and Carr (2005) showed that propagation conditions in July were as good as or better than those estimated for June. The strong subsurface sound channel formed by the CIL was not input into the RAM and may have resulted in the underestimation of the predicted levels. Austin and Carr (2005) demonstrated that field measurements and model estimates can show good agreement, although for their comparison the RAM transmission losses were remodelled with oceanographic data taken during the seismic survey and source levels from the array actually used. They also presented data indicating large discrepancies (up to 10 dB)

between estimated and measured sound levels for particular frequency bands and locations, indicating that some local environmental variability was not captured in the model. Our data showed that the specific characteristics of the regional sound propagation, such as the shadowing produced by the Sable Island Bank, can significantly affect expected sound levels. This underlines the importance of conducting extensive field validation under a variety of conditions.

There is also a need to have some measure of the variability around the model estimates. Deterministic transmission loss models provide no indication of uncertainty and must be used with caution. Sources of uncertainty will not only include the variable and possibly inaccurate physical parameters in the propagation model but will also include pulse-to-pulse variation of the seismic array. To avoid exposing animals to higher-than-expected energy pulses, a wide buffer should be added to the estimated safety zone to reflect the margin of error. The present study has shown that errors on the order of 10 dB or more are not unusual.

Although SPL_{rms} is the most common unit used to compare sound levels between studies, this metric varies considerably depending on the width of the estimated pulse time window and can be considerably underestimated. This point is well illustrated by the major differences between SPL_{rms} and peak sound levels (Table 1). In the present study, the mean peak level was 15 dB higher than the mean SPL_{rms} and SEL. This gap was in part due to the difficulty in defining the RMS time window, since many of the pulses were drawn out in time, thereby reducing the SPL_{rms} estimate. Our analyses showed that the inter-pulse variation in SPL_{rms} could be as high as 10 dB over many stations. When pulses were clearly defined, i.e., with few multi-path echoes, such as for stations E2 and E3, the SPL estimates were clearly higher, and the difference between the peak, SPL and SEL was approximately 10 dB each, as discussed by Malme et al. (1984). This suggests that the mean SPL_{rms} is not the best metric for the description of the received level of pulsed sounds.

CONCLUSIONS

From this study, several conclusions can be drawn:

- The highest average sound pressure level (RMS) measured in the Gully MPA was 145 dB re $1\mu Pa$ at 90 m depth, 50 km from the seismic array. This sound level was measured within the Gully Whale Sanctuary while the seismic vessel was surveying the western portion of the exploration block. It was estimated that sound levels in the Whale Sanctuary would have been higher, between approximately 153 and 157 dB, when the vessel was at its closest approach to the Gully in the eastern portion of the survey block. The “worst case” sound level at the Gully MPA boundary, i.e., 0.8 km from the source, can be estimated from the extrapolation of near-field measurements in Austin and Carr (2005) to be approximately 178 dB, 14 dB higher than predicted in Moulton et al. (2003).
- Models predict average conditions and do not capture the spatial and temporal variability of the real environment. Measured sound levels were significantly higher

than the model predictions at several stations. In addition, the range of audibility of seismic pulses to a mid-sized odontocete similar to a northern bottlenose whale was significantly underestimated relative to the model predictions. This demonstrates the importance of using accurate model input data, the importance of field validation and the need to have a measure of the variability around the mean sound level estimates. Transmission losses should be re-modelled if actual field conditions differ from assumptions.

- Sound pressure levels (RMS) varied considerably in relation to the width of the estimated pulse time window, which was dependent on the magnitude of multi-path arrivals. Although SPL_{rms} is the standard measurement for comparison to safety limit criteria for marine mammals, it is not a good metric for the description of pulsed sounds due to the inconsistency of the pulse time window.

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