Model based sound level estimation and in-field adjustment for real-time mitigation of behavioural impacts from a seismic survey and post-event evaluation of sound exposure for individual whales

Roberto Racca (1), Alexander Rutenko (2), Koen Bröker (3) and Glenn Gailey (4)

(1) JASCO Applied Sciences, Victoria, British Columbia, Canada
(2) Pacific Oceanological Institute, Vladivostok, Russia
(3) Shell Global Solutions, Den Haag, The Netherlands
(4) Texas A&M University, Galveston, Texas, USA

ABSTRACT

While it is common practice to use sound propagation modelling to estimate the safety shutdown radius around a seismic survey source, only rarely are numerical estimation methods applied to the real-time mitigation of behavioural effects that occur at much greater ranges. For a seismic survey in 2010 near a critically endangered whale population on their feeding grounds, a strategy was implemented for the prediction and field calibration of behavioural safety boundaries that were used for shutdown decisions by shore and vessel based observers equipped with ranging instruments and geo-referencing software. This summary paper describes the steps involved in the estimation, selection and validation of the noise boundaries for different survey lines and under variable propagation conditions. Results of post-event analyses to estimate sound exposure levels and other acoustic parameters of the received seismic pulses along the paths of visually tracked whales are also presented.

OVERVIEW

A 4D seismic survey was conducted for Sakhalin Energy Investment Company Ltd during the period from 17 June to 2 July 2010 offshore the Astokh region of north-eastern Sakhalin Island, in the Russian Far East. This area includes the summer feeding grounds of the Western Grey Whale (*Eschrichtius robustus*), an endangered population. A total of 35 survey lines were acquired (see Figure 1), some of them requiring repeat passes because of technical issues with the survey, interruptions related to weather and visibility, or shutdowns due to the presence of whales in critical regions.

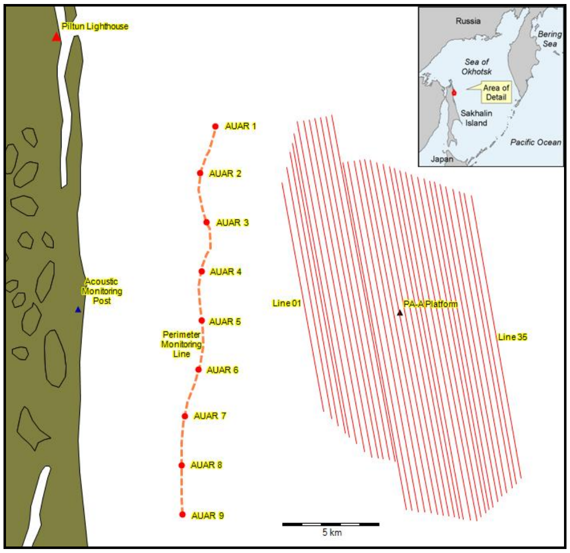

Figure 1. Layout of the 2010 Astokh 4D seismic survey lines and Perimeter Monitoring Line with nine acoustic sensors.

Throughout the survey a field team of scientists supported by the oil & gas company put into action a sophisticated noise exposure mitigation plan, developed through a multidisciplinary effort (*Report of the 4-D Seismic Survey Task Force*, 2010), which relied on an extensive pre-operation numerical modelling of the acoustic footprint of the seismic airgun array for a large number of source positions along each acquisition line. This preparatory work generated a comprehensive library of predictive model cases that covered a broad range of potential sound propagation conditions through a combination of different acoustic medium parameters and sound level offset adjustments.

Two types of modelling results were used in the field for distinct purposes. The first were sequences of estimated per-pulse Sound Exposure Level (SEL) values at the sea floor, indexed by source run distance along a survey line, at the sites of nine bottom-deployed acoustic telemetry stations (Figure 1). These sequences were used by the acoustics monitoring team to select a model case best matching the received pulse levels during the initial minute of a line acquisition, and thereafter to monitor and verify the accuracy of the model estimates as the seismic vessel progressed along the line. The second were static outline maps of the estimated shoreward 156 dB re $1\mu\text{Pa}^2$-s per-pulse SEL behavioural threshold (*Report of the 4-D Seismic Survey Task Force*, 2010), maximized over depth, for each survey line. These outlines, overlaid on specialized GIS-based software for cetacean tracking, provided to observer teams a reference boundary defining whether a located animal was in a region where sound levels were considered liable to elicit behavioural disturbance.

Following completion of the survey, further studies were conducted to estimate the pulse sound levels that would have been experienced by the each of the whales visually tracked by the behaviour monitoring teams. The approach was once again a hybrid of model based estimation and correction from field-collected sound level data. By comparing the model estimates of per-pulse SEL at the sites of the bottom-deployed acoustic stations with the corresponding measurements logged in the field, adjustment factors were computed and applied to the modelled estimates at the whale locations. This not only yielded an increased accuracy of exposure level estimation over modelling alone, but also enabled the estimation of received levels during the ramp-up periods at the start of every survey line which would have been problematic to model analytically.

SOUND FOOTPRINT ESTIMATION STRATEGY

Advance modelling of sound propagation cases

The airgun source level model AASM (MacGillivray, 2006) was used to generate the close-range directional acoustic footprint for the airgun array configuration to be deployed for the acquisition of the seismic lines. The directional levels were input to the acoustic propagation model MONM, developed by JASCO as an extension of the Parabolic Equation code RAM (Collins, 1993) to generate long-range sound level contours for several tens of source points along each seismic survey line. The shoreward envelope (maximum extent) of the individual contours for the 156 dB re 1µPa^2-s per-pulse SEL behavioural threshold, maximized over depth, defined the static outline of the protection zone for that seismic line. Because the propagation conditions could be expected to differ from the default case postulated on the basis of earlier studies and also vary over the course of the survey, a range of outlines corresponding to different propagation regimes and level adjustments were generated before the field season and stored in a file database. Figure 2 shows how the boundary of the protection zone for the most nearshore line of the seismic survey could be expected to vary according to propagation conditions within a range of feasible cases considered in the modelling. A library of such cases for all the survey lines was brought to the field operation.

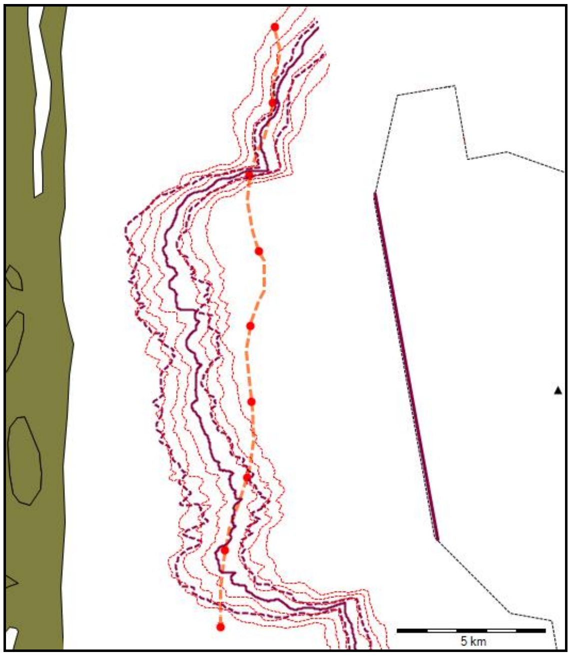

Figure 2. Behavioural protection zone boundaries for the most nearshore survey line under standard, low, and high propagation regimes (solid and dashed blue outlines) infilled by finer level adjustments in 1 dB steps (thin red outlines).

Acoustic monitoring configuration

An underwater network of autonomous real-time acoustic measurement nodes (AUARs) was deployed along a sinuous line roughly parallel to the shore, extending some 20km in the north-south direction approximately at the 20m bathymetry contour (Figure 1). This Perimeter Monitoring Line (PML) was based on the best available historical estimation of the distribution bounds of the Western Grey Whale population in the region at the time of the survey (*Report of the 4-D Seismic Survey Task Force*, 2010). It consisted of nine AUAR digital acoustic recorders (16-bit, 30 kHz sample rate) installed on the sea floor with radio telemetry of a subsampled waveform (~4kHz rate) provided via tethered transmitting buoys. These units were built, deployed and maintained by members of the acoustics group at the Vladivostok based Pacific Oceanological Institute (POI). Figure 1 shows the layout of the PML relative to the coastline and the Astokh 4D survey lines. The telemetry reception and signal processing equipment used by the shore based acoustics team was housed in a small laboratory hut built just above the beach half-way along the length of the PML to optimize radio transmission ranges. Directional dipole antennae mounted on tall masts and trained on the bearing of each AUAR provided good RF reception gain, maximizing sensitivity to the signals broadcast by the buoys on low-gain omnidirectional whip antennae. The VHF band radio signals were tuned in on commercial marine receivers and the modulated audio output was processed through digital decoders of POI design that reconstructed the original acoustic pressure time series. The nine channels of digital data were archived to disk and processed by a front-end computer for spectral characterization, then streamed in one-minute batches over a local network to an independent system for the airgun array pulse level analysis and model estimates verification described in this article. In parallel with the acoustic monitoring, the coordinates of all vessels operating around the survey area were acquired with an AIS (Automatic Identification System) receiver and displayed on a GIS map for immediate interpretation of the activities as well as logged to disk for future reference.

Model case selection and real-time verification

As the seismic vessel lined up for the acquisition of a line, it would gradually ramp up the airgun array source by activating progressively more airguns. This ramp-up had the dual purpose of mitigating the risk of exposing a whale suddenly to a high acoustic pressure level and of purging the airguns of any ice from moisture in the compressed air supply so that they would operate regularly during the actual run. The occasional misfirings due to ice formation as the airguns were brought on-line made the ramp-up levels somewhat variable, a reason why their analytical estimation would have been difficult. The acoustics field team monitored the received pulses at the PML stations on a multichannel display that also indicated through highlighting the successful detection and sound level processing of each pulse. When the seismic vessel reached the start of the line, it would inform by radio the acoustic team on shore who would begin logging the received pulse levels from the AUARs. The pulse levels from the first minute of acquisition (usually around 6-7 readings per channel) at the three PML sites closest to the line start point were used for the selection of the best model case for that line run. This was done through a spreadsheet application that compared the average measured pulse levels at the three PML stations to the predicted levels at the same sites from model scenarios corresponding to standard (base), low and high sound propagation regimes. The software would display the propagation regime and a decibel offset (jointly referred to as a “model case”) that resulted in the smallest residual between the forecast and measured start-of-line levels.

Upon selection of a model case (typically in less than five minutes from the starting of the survey line) the acoustic monitoring team would broadcast the active case identifier to three visual observation teams (two based at tower platforms on the shoreline and one on a spotter vessel) through an established protocol of two-way radio communication relays. The observation teams would then retrieve from a locally stored database the corresponding pre-modelled protection zone boundary which would be displayed as a map overlay in a specialized cetacean tracking software application. This software processed visual observation fixes from theodolites and reticle binoculars into geo-referenced coordinates on a map, allowing the teams to assess within seconds whether a whale sighting was within or outside the estimated region of potential behavioural effect and react according to the response procedures in the monitoring and mitigation plan.

Following the broadcast of the selected model case, the acoustic monitoring team would turn their attention to the real-time verification of its ongoing suitability. During the acquisition of a seismic line the team could visualize through a custom software application a real-time chart of the received pulse level traces at all the PML stations as a function of the source vessel progress along the line. The application screen would also show the corresponding estimated pulse level trace at a user selected PML station for the active model case, allowing a direct comparison between model and measurement at a given sensor. In a typical line run the acoustic monitoring team would select sequentially for verification the telemetric sensor most proximal to the current position of the seismic vessel, as it would be measuring the dominant across-track (broadside) beam of the airgun array that shaped the reach of the estimated shoreward sound level boundary. The active model case was deemed to be in compliance with the mitigation plan directives if the measured pulse level trace – exclusive of jitter and transient oscillations – remained solidly within a tolerance band of +3 dB from the modelled trace. A violation of this condition would have meant that the current sound level boundary being used by the visual observation teams was no longer applicable and would have to be updated with another library case. This situation never occurred throughout the survey aside from a couple of revision calls during the initial section of the first line, caused more by unfamiliarity with the starting trends of the pulse level traces than by an actual divergence of the model estimates.

ESTIMATION OF LEVELS ON WHALE PATHS

Analyses of the data collected during the survey, both acoustic and observational, are ongoing. The aim is to examine potential relationships between sound levels and whale behaviour, while considering other factors that could equally affect the animals, through a rigorous multivariate analysis (MVA). To that end the variables that may affect behaviour must be quantified at the location of the whales. During the survey accurate positional information was collected for numerous whale paths by behavioural monitoring teams, and the location of all vessels in the immediate area was recorded through AIS/GPS logging. From these data it is possible to model the sound levels from the airgun source and the vessels as received at the whale locations, using the same propagation parameters found to be appropriate for a particular line run as described earlier. This estimation process has yielded detailed time histories of sound levels at whale locations, an example of which is given in Figure 3, that mimic to some extent the data that could be collected through recording tags attached to the animals (a notable difference being the lack of dive depth information between surface sightings, which forces the sound level estimates to be based on maximum over depth).

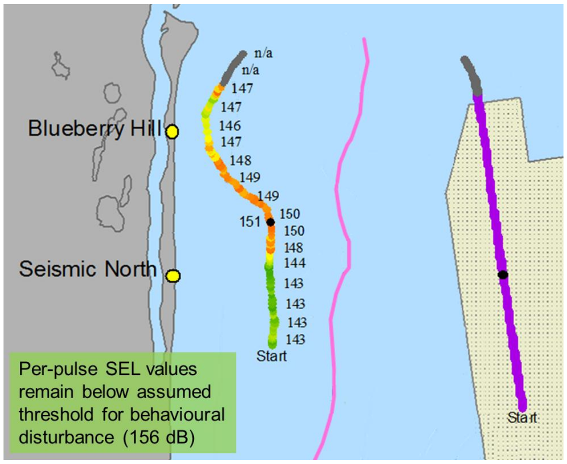

Figure 3. Whale path annotated with estimated sound levels (per-pulse SEL) from the seismic survey line on the right. The simultaneous start points of the two tracks are labelled, and black bullets denote the locations of source and whale at time of maximum exposure. Shown on shore are two behavioural monitoring stations from which whales were tracked.

While the original estimation process – including the example shown above – relied on modelling alone, the algorithm has more recently been enhanced to use the sound level information from the archival recordings at the PML to apply correction terms based on the difference between model estimates and measurements at the station closest to the whale position. This method also allows the estimation of sound levels during ramp-up, letting the correction term address the variation in source intensity. Further extensions of the approach are being used to enable the estimation on whale paths of other pulse metrics that cannot easily be modelled directly.

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