WESTERN GRAY WHALE ADVISORY PANEL
9th Meeting
PUBLIC

WGWAP 9/18
4-6 December 2010
ENGLISH

SEIC 2010 Astokh 4D Seismic Survey,
Comparison of modelling and monitoring results

Submitted by: SEIC

Sakhalin Energy Investment Company, Ltd
Controlled Document

Sakhalin II Assets

	Asset	Origin	Module	Discipline	Doc Type	Doc No.	Sheet No.	Rev No.
Document Number:	1000	S	90	04	T	0708	00	01

Title:

Sakhalin Energy 2010 Astokh 4D Seismic Survey
Comparison of modelling and monitoring results

Custodian: *Doug Bell, Environmental manager*	Classification: *Unclassified*

Issue Purpose				
	I/FR	For Information/Review	SUP/OBS	Superseded / Obsolete
	AFD	Approved for Design	ASB	As-Built
	AFC	Approved for Construction	PUR	Issued for Purchase
	AFU	Approved For Use	ENQ	Issued for Enquiry

Rev	Issue Purpose	Description	Originator: Name (Company) / Checked by: Name (Company) / Approved by: Name (Company)	Signature	Date
01	AFU	*Approved for Use*	*Originator:* Roberto Racca *(Jasco App. Sciences)*		29 Nov. 2010
			Checker: Doug Bell *(Sakhalin Energy)*		
			Technical Assurance: Doug Bell *(Sakhalin Energy)*		
			Approver: Richard Evans *(Sakhalin Energy)*	[signature]	

Location of Change	Brief Description of Change to Latest Revision
	(For the new /current revision)

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Sakhalin Energy 2010 Astokh 4D Seismic Survey Comparison of modelling and monitoring results

Summary Report version 1.1
Date: 03-Dec-2010

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Principal author: Roberto Racca
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1. Introduction

During the period from 17 June to 2 July 2010 a 4D seismic survey was conducted offshore the Astokh region of north-eastern Sakhalin Island. A total of 35 survey lines were acquired, some of them requiring repeat passes (complete or partial) because of technical problems, interruptions related to weather and visibility, or mitigation shutdowns due to the presence of whales in critical regions. Throughout the survey a mitigation plan based on recommendations of the Seismic Survey Task Force [1] was enacted that relied on an extensive pre-operation numerical modelling of the acoustic footprint of the seismic source at a large number of locations along each acquisition line. The results of this modelling as utilized in the field had two distinct but intrinsically related embodiments. The first were static area maps of the estimated 156 dB re 1µPa^2-s* per-pulse Sound Exposure Level (SEL) shoreward front, maximized over any water depth, for each survey line. These maps were used by the visual observation teams as templates for determining whether a located animal could be at risk of being exposed to a behaviourally significant sound level. While essential to the enforcing of the mitigation criteria, they were irrelevant to any kind of validation in the field since no real time measurement could directly corroborate the estimated acoustic front. The second embodiment of the model output were KP (distance along a line) indexed charts of the estimated per-pulse SEL at the sea floor at the sites of 9 underwater acoustic telemetry stations. These charts were used by the acoustics monitoring team to select a model case best matching the received pulse levels during the initial moments of a survey line acquisition, and thereafter to monitor and verify the accuracy of the model estimates as the seismic vessel progressed along the line. The present report is largely devoted to the outcome of such selection and verification of model cases in the field.

2. Real-time sound monitoring configuration

At the core of the acoustic monitoring and mitigation methodology was a real-time underwater sound measurement network known as the Perimeter Monitoring Line (PML) whose layout 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 [1]. This network of autonomous nodes lay along a sinuous line roughly parallel to the shoreline, extending some 20km in the north-south direction approximately at the 20m bathymetry contour. It consisted of nine bottom installed AUAR digital acoustic recorders with radio telemetry capability 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) led by Dr Alexander Rutenko. Figure 1 on the next page shows an overall map of 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 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 omnidirectional whip antennae. The VHF band radio signals were picked up on commercial synthesized tuning receivers (scanners) and the modulated audio output was processed through digital decoders of POI design that reconstructed the original 16-bit, ~4kHz

* In the remainder of this document the reference term 1µPa^2-s of SEL values in dB will be implied.

sampled acoustic pressure time series. The nine channels of digital data were archived to disk and processed by a POI computer for spectral characterization, then streamed over a wireless local network to a JASCO system for airgun array pulse level analysis. 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.

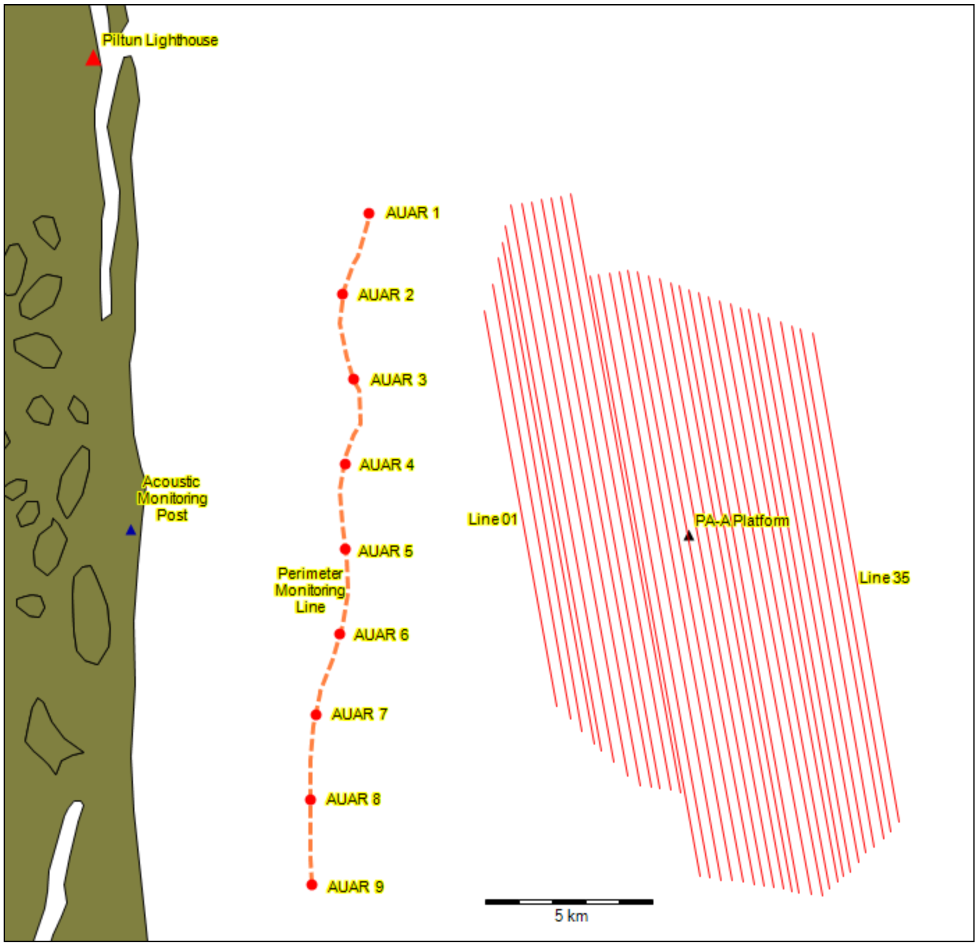


Figure 1 - Map of the Astokh coastal region of Sakhalin Island showing the relative layout of the 2010 seismic survey lines, the Perimeter Monitoring Line network of AUAR telemetric recorders, and the shore based acoustic monitoring post.

3. Start of line model case selection

As the seismic vessel lined up for the acquisition of a line, it would gradually ramp up the airgun array source for the dual purpose of mitigating the risk of having an animal exposed suddenly to a high acoustic pressure level and of clearing the airguns of any formation of ice from moisture in the compressed air supply so that they would operate regularly during the actual run. The JASCO acoustics field team monitored the received pulses at the PML AUAR units on a multichannel display, shown in the main window in Figure 2, that also indicated through highlighting the successful identification and sound level processing of each pulse (a second software application, whose output appears in the inset window, allowed the tracking and verification of the received levels trends against model estimates as described later in this report). When the seismic vessel reached the first acquisition point on a line, the survey superintendent would inform by radio the acoustic team who would begin logging the received pulse levels at all the PML sites. The levels at three of the AUARs, generally the closest one to the line start and the adjacent ones on either side (which depended on the direction of sailing of a line as well as its length), were used for the selection of the best model case for that line run as explained below.

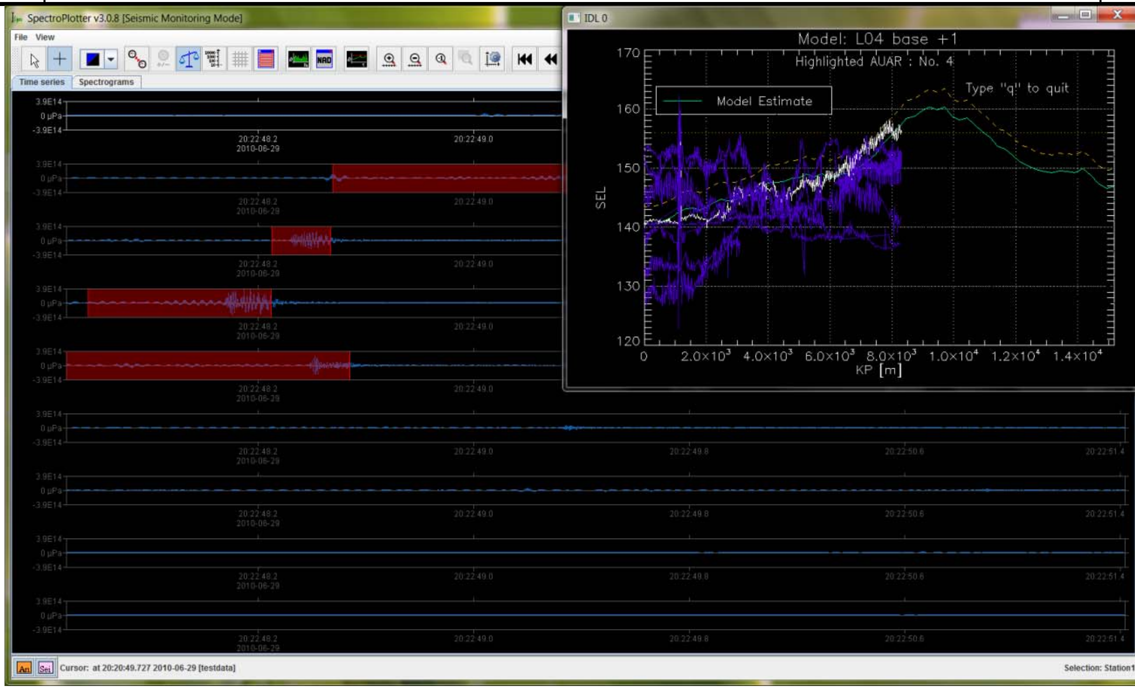


Figure 2 - Field computer screen shot showing the visual output of the real-time seismic pulse monitoring software (main window) and pulse level tracking and validation software (inset window) during the acquisition of line 04.

The first minute of per-pulse SEL levels (7 or so readings per channel) at the designated start-of-line PML receiver sites were copied from the logs of the real-time monitoring software to a spreadsheet application programmed to compare the average measured pulse levels at these locations to the predicted levels at the same sites from model scenarios corresponding to base, low and high sound propagation regimes [1]. The algorithm would select a model scenario and a decibel offset (jointly referred to as a “noise case”) that resulted in the smallest residual between the forecast and measured start-of-line levels. An example of noise case selection for Line 04 (sailed south to north) is shown in Figure 3.

L04							
29-06-2010	19:23						
	L04	AUAR 9	AUAR 8	AUAR 7	dB offset	Residual	**Noise case**
	base	146.4	152.7	147.8	1	4.05	**L04_base+1**
	high	148.0	153.2	149.2	-1	4.91	
	low	144.7	150.3	146.4	2	4.31	
	Measured	145.0	153.3	150.4			
	Calculation	144.1	152.8	151.1			
		146.7	153.3	150.6			
		144.0	152.9	151.2			
		146.9	153.7	150.0			
		143.3	153.3	150.5			
		146.2	153.8	149.5			
		143.6	153.5	149.8			

Figure 3 - Sample noise case selection spreadsheet showing the start-of-line levels for line 04 as measured at the PML and estimated from different propagation modelling scenarios. The resulting noise case is displayed in the right column.

Immediately upon completion of the selection procedure (generally within about five minutes from the starting of a survey line) the acoustic monitoring team would broadcast the active noise case to all visual observation teams on shore and at sea through an established protocol of radio communication relays. The observation teams would then select from a digital library the corresponding noise front area map and use it in the assessment of any sightings according to the monitoring and mitigation plan.

Table 1 summarizes the noise cases selected on the basis of initial pulse level measurements at the PML for each of the lines in the survey. It is readily observed that all three of the propagation regimes emerge in the selections as most appropriate for different lines, a fact that belied the original expectation that one model scenario best matching the physical environment at the time of the survey would dominate the selection roster. In a later section of this report the distribution and trends of the selected noise cases will be examined in the light of preliminary results from hydrographic studies.

Table 1 - Noise cases (propagation regime and offset) selected for each line in the survey. Line 12 has two entries as it was run in separate segments a few days apart with different noise case selections.

Line	Start date	Start time	Propagation regime	Offset (dB)		Line	Start date	Start time	Propagation regime	Offset (dB)
1	23-06	14:06	base	+1		18	01-07	01:59	base	+1
2	19-06	10:04	base	+3		19	02-07	04:06	high	-1
3	27-06	07:52	low	+3		20	02-07	13:36	high	-1
4	30-06	21:44	base	+1		21	29-06	11:51	low	+2
5	26-06	15:02	high	-2		22	23-06	09:08	base	+0
6	28-06	16:26	base	+1		23	28-06	11:21	base	+0
7	01-07	06:50	base	+2		24	18-06	11:18	low	+4
8	01-07	22:58	base	-1		25	23-06	17:35	base	+1
9	28-06	06:13	low	+3		26	24-06	01:48	base	+1
10	29-06	06:29	low	+3		27	19-06	06:16	high	+0
11	18-06	06:03	high	+1		28	22-06	12:33	low	+2
12	25-06	21:05	base	+1		29	30-06	13:55	low	+2
	30-06	06:00	base	+2		30	26-06	10:47	base	+2
13	24-06	18:48	low	+0		31	19-06	22:46	low	+4
14	26-06	19:15	base	+0		32	24-06	09:19	base	+2
15	25-06	04:03	base	+0		33	20-06	21:25	high	-1
16	26-06	02:31	base	+1		34	18-06	22:45	base	+3
17	29-06	23:55	high	-2		35	22-06	21:06	base	+1

4. Comparison of A-lines zone boundary

The library of pre-computed model results brought into the field spanned what was considered to be a reasonably wide set of propagation conditions on either side of the *a priori* default scenario, a “base case” corresponding to a set of modelling parameters that has been used over the years for the estimation of received levels from industrial operations in the Piltun-Astokh region and generally found to be in good agreement with measurements. The model, however, had not been previously used for the forecasting of sound propagation under very early season conditions, when the acoustic environment and in particular the water sound speed profile may be significantly affected by thermal and salinity variations associated with the very recent presence of sea ice over the surface. A sound speed profile representative of early season measurements had been used for the base case, and it was thought that the default scenario would have provided a realistic estimation of propagated sound level footprints shoreward of the survey at least under average hydrological conditions. Based on these assumptions a map of the “A-lines zone” [1] was defined in advance of the survey to allow a planning stage estimation of the size of the survey area over which the more stringent mitigation rules associated with the "A" sections of the seismic acquisition lines (where the 156 dB per-pulse SEL noise front was estimated to extend shoreward of the PML) would be applicable. For every noise case that would result in an "A" component the operational transition point had been pre-mapped by projecting onto the survey line the extreme point where the 156 dB SEL front intersected the PML and then lengthening the "A" section by a 500m precautionary buffer. The pre-season "A-lines zone" was bounded by the locus of such transition points for the default or "base plus zero" noise cases. In the course of the survey the effective A-lines zone was defined progressively as noise case selections were made for individual lines. Figure 4 below shows the original boundary as a solid outline overlaid on a shaded area denoting the effective zone. The latter generally extends some distance beyond the bounds of the former, indicating that the default propagation "base case" did in fact slightly under-estimate the conditions encountered in the field. A notable exception is the notch in the effective A-lines zone boundary corresponding to the eighth line from shore (Line 08) indicating that the transition point to the "A" mitigation regime occurred some 3km farther along the line than the pre-season default modelling had estimated. Referring to Table 1 it is readily seen that the noise case selected for the line in question was in fact uncommonly low (1 dB below the base case). Line 08 was acquired in especially critical conditions, as its "B" section had been scheduled to be run at night subject to pre-dusk scouting of the area and the remaining "A" section would be run in the morning just ahead of a forecast deterioration of weather conditions and visibility. The decision to run the "B" acquisition to the full extent of the selected noise case was made subject to very strict tracking of the instantaneous pulse levels at the PML, whereby an early halt would have been called if the trends indicated that the 156 dB SEL per-pulse threshold was likely to begin extending shoreward of that boundary. As will be seen in the next section the real-time tracking of the levels did confirm the correctness of the low propagation noise case; the "B" section of the line was thus acquired at night up to the nominal transition point at which time a default shutdown was performed by the seismic vessel as prescribed by the mitigation protocol.

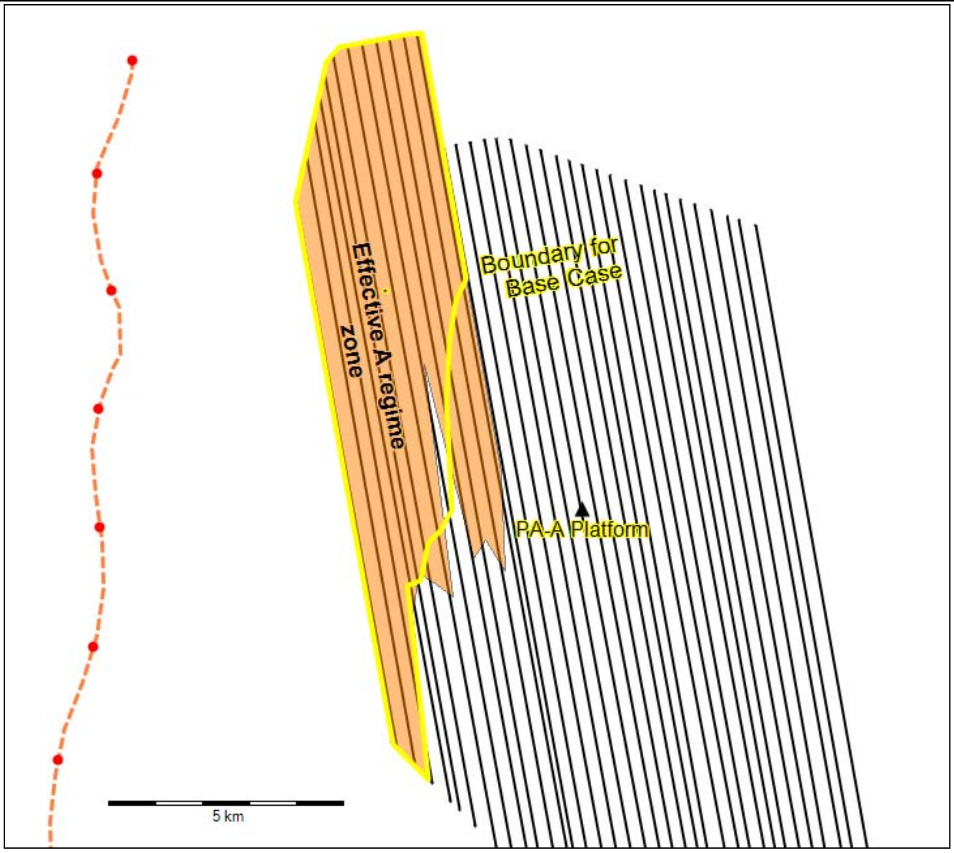


Figure 4 - Extent of A-lines zone as originally assumed from default or "base case" propagation modelling conditions (solid outline) and as effectively implemented during the survey based on noise case selections for individual lines (shaded area).

5. Comparison of tracked levels at the PML

5.1 Real-time pulse levels management

As already gleaned from Figure 2 (the relevant detail of which is reproduced in Figure 5 for convenience), the acoustic monitoring team in the field had constantly available during the course of a seismic line acquisition an overall view of the received levels trends at any of the PML sensors and their corresponding model estimates from the selected noise case. This served the dual purpose of monitoring in absolute terms the per-pulse level at the perimeter line to ensure that it remained below 156 dB SEL while acquiring any line under the less stringent "B" mitigation rules [1] and of ensuring that the active noise case as selected at the beginning of the line kept providing an acceptable estimate of the shoreward propagating acoustic levels from the seismic source. The latter meant that the visual observation teams using static sound level front maps for the same noise case would have the correct information on which to base mitigation decisions. The solid green curve in Figure 5 is the

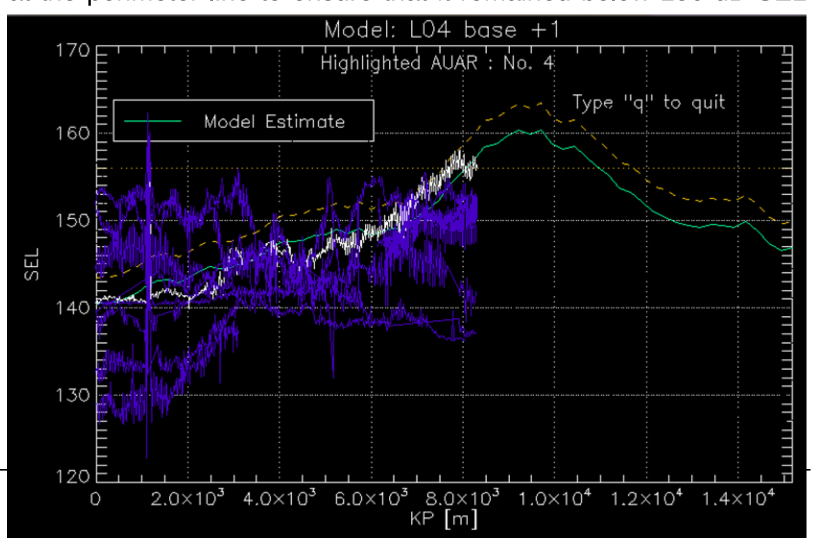
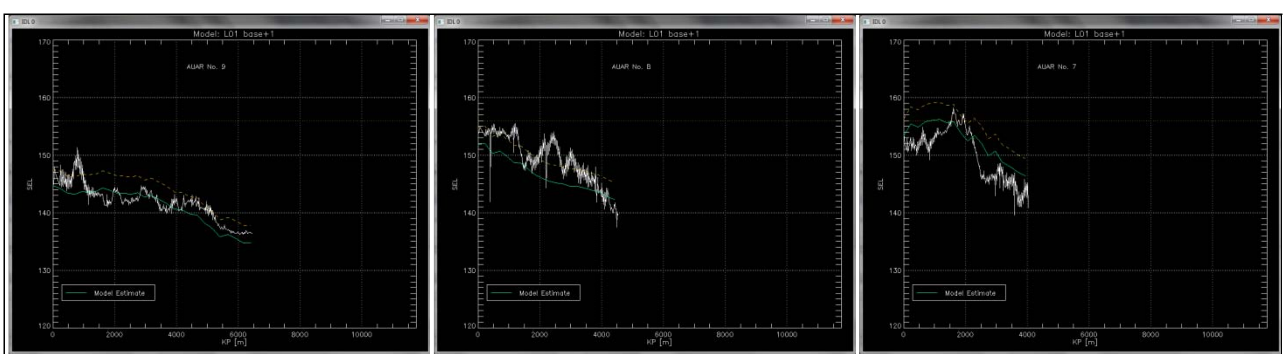


Figure 5 - Detail screen shot of real-time pulse level tracking and validation software during acquisition of a seismic line.

model predicted level at a user selected PML sensor, which was normally set to the AUAR most proximal to the current position of the seismic vessel. Selecting a sensor also highlighted in white the pulse levels trace from its data, while corresponding traces from the other sensors remained visible in blue to allow an ongoing watch for anomalous events at more distal sites. As an aide to the task of validating the suitability of the current noise case, a +3 dB offset trace of the model predicted level also appears on the software screen (dashed curve in Figure 5); this represents the “tolerance band” within which measured levels could exceed the model prediction without prompting a reassessment of the noise case choice as per the agreed mitigation protocol [1]. In fact the protocol specified a strict tally-based compliance with the +3 dB tolerance (not to be exceeded by more than three pulses out of every ten); under realistic conditions this was found impossible to implement due to the significant jitter and short-term oscillations of the pulse levels traces. The tracked real-time levels were therefore considered to be in compliance (in the sense of not triggering a reclassification of a noise case) as long as the trend exclusive of jitter and transient oscillations remained solidly within the tolerance band. Tighter control of the traces was applied in succession to the PML sensors most proximal to the advancing seismic source, where received levels could approach (or exceed in the case of “A” sections of lines) the 156 dB SEL threshold. Under no circumstances would surges above that threshold be allowed for a seismic line being acquired under “B” mitigation rules.

5.2 Post-survey review case: Line 01

Line 01 was acquired on 23 June, a few days into the Astokh 4D seismic survey. It was by default classified as a full “A” line – requiring a stricter set of mitigation criteria which included daylight and good visibility conditions – and was completed uneventfully in a single run lasting slightly more than an hour. Its interest as a review case lies in its location at the westernmost edge of the survey area, with significant projection of the 156 dB per-pulse SEL noise front shoreward of the PML. To facilitate this post-survey review the real-time display of Figure 5 was pared down to show only the pulse levels trace for the selected sensor, along with the model estimate curve and +3 dB tolerance band. The display of the traces is also limited to a range of interest along the KP axis bounded by the points where the estimated levels drop to 10 dB below the CPA maximum or 150 dB SEL, whichever is less. This focuses the comparison of measured and model based levels to a region where discrepancies would have the potential to be operationally relevant. Figure 6 shows the pulse levels traces over their respective regions of interest in a series of display screens corresponding to the successive PML receivers. It is apparent from these traces that the measured pulse levels exhibit considerable jitter and transient variability that can cause fairly substantial local mismatch. It is also evident on the other hand that the model estimates, computed well before the survey and unvaryingly only matched to measurements over a few pulses at the start of a run, do by and large keep matching the observed trends with good accuracy through the full length of the line.



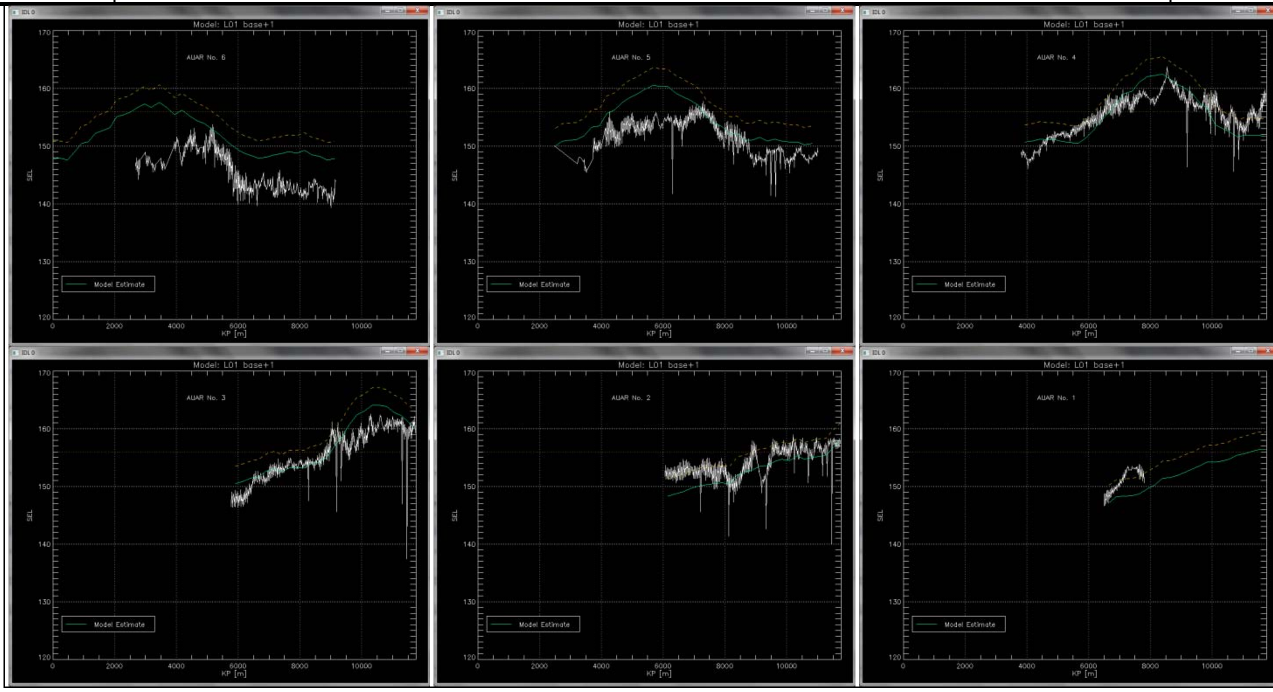


Figure 6 - Overlapping piecewise display of measured pulse levels and comparison to modelled trace for noise case base + 1 at successive PML acoustic sensors (top left to bottom right: AUAR 9 to AUAR 1) for seismic line 01.

The measured pulse level traces for PML receivers 6 and 5 (first and second frames in the middle row of Figure 6) are noticeably lower than the model estimates than is the case for any of the other sensors. A sag in the observed levels at these AUAR units as the seismic source transited past them was in fact observed consistently throughout the survey and led the acoustics field team to conjecture that the propagation path of the pulses to these receivers was affected by some local feature of the seafloor (like an underwater sand ridge) not represented in the bathymetry dataset used for the modelling. Hydrographic studies performed by POI [2] during the survey period and currently being documented have since confirmed the localized presence of sound blocking bottom ridges, which may indeed change from season to season under the influence of powerful storms. These are unlikely to affect enough of the water column to alter significantly the overall propagation footprint as estimated, but may affect significantly the readings of individual bottom deployed hydrophones.

5.3 Post-survey review case: Line 08

Line 08, acquired in the night of 1 July and the morning of 2 July in separate runs, is also worthy of detailed review because of its first portion having been executed under conditions of no visual monitoring capability for the full length of the model estimated "B" section. This required especially thorough acoustic monitoring of received pulse levels to ensure that the noise case selected, and the consequent location of the mandatory shutdown point at the transition to the "A" section, was well supported by the sensor data. Figure 7 presents the pulse levels traces over their respective regions of interest as previously described; the top two rows contain the traces for receivers 9 to 4 during acquisition of the "B" section, while the bottom row shows the traces for receivers 4 to 2 during acquisition of the "A" section. The noise case for the later run was carried over from the selection made at the start of the line and verified to be still consistent with the measured levels. As it can be observed from the traces, the pulse levels at successive PML sensors rose in good agreement with the model estimates as the acquisition of the "B" section progressed and were just hovering near the 156 dB SEL threshold at AUAR 4 when the vessel called a technical halt at the predefined transition point. The match over the later "A" section acquisition was equally good and the line was successfully completed under the original noise case.

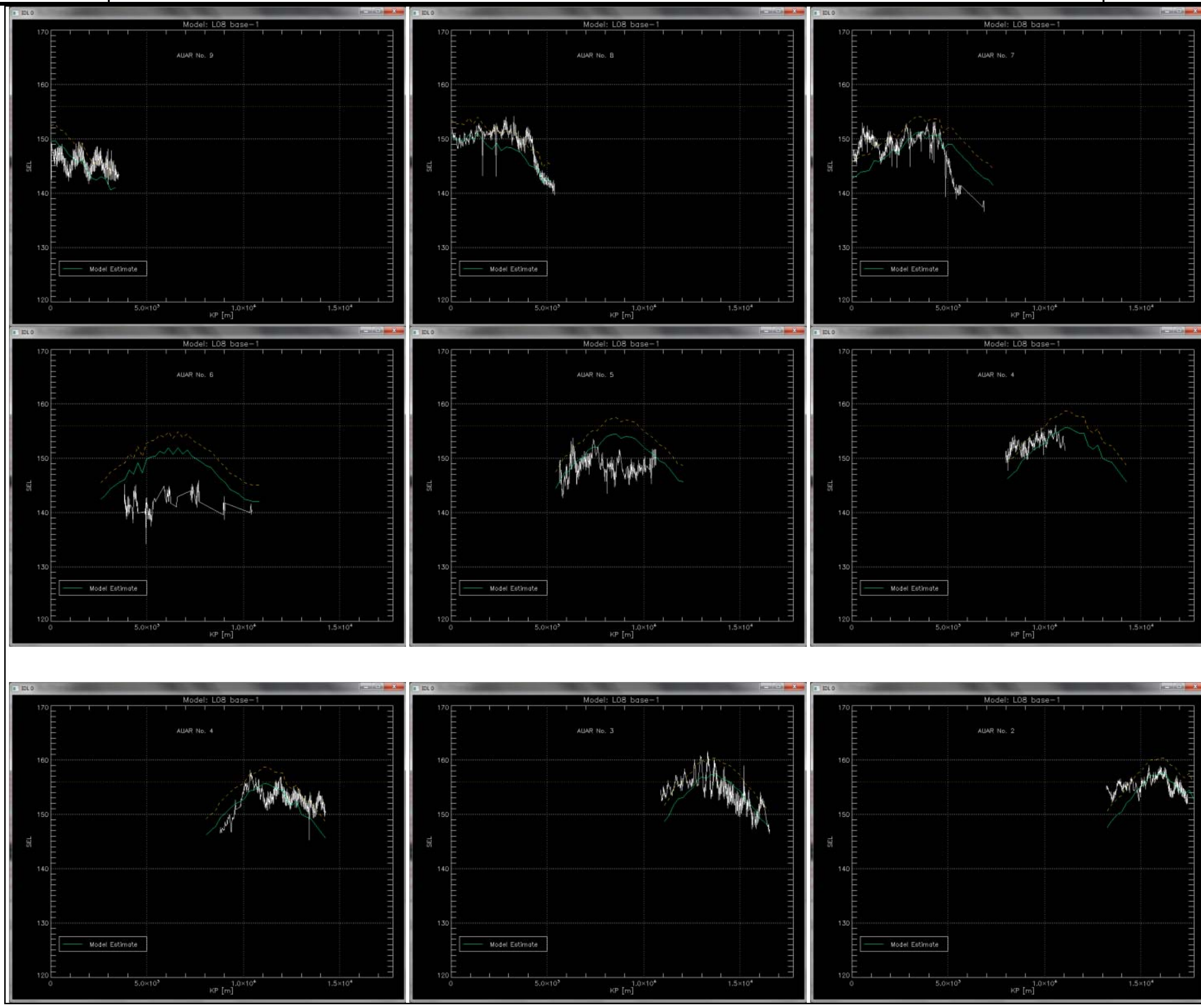


Figure 7 - Overlapping piecewise display of measured pulse levels and comparison to modelled trace for noise case base - 1 at successive PML acoustic sensors for seismic line 08. The top six charts (top left to bottom right: AUAR 9 to AUAR 4) show the levels during the acquisition of the “B” section of the line late at night; the bottom three charts (left to right: AUAR 4 to AUAR 2) show the levels for the remaining “A” section acquired in the morning.

5.4 Post-survey overview of runs in A-lines sector

To facilitate an overview of the comparison between monitored pulse levels and their modelled estimates for complete survey lines, the paradigm of the real-time display in Figure 5 was further modified by limiting the KP range of interest for each PML receiver to the immediate neighbourhood of its closest point of approach (CPA). Since the receivers are nominally spaced 2.5km, non-overlapping regions of interest for piecewise display of traces were defined as 1.25km on either side of each CPA. Figure 8 presents this consolidated full-line display for lines 01 to 10, 12 and 13. These are all the runs in the A-lines sector except line 11 (an early run tracked with some glitches) as well as the most shoreward of the full “B” lines.

Figure 8 - Piecewise display of measured pulse level traces and corresponding modelled estimates near the CPA of successive PML sensors. Top left to bottom right: seismic lines 01-10, 12 and 13 (operationally labelled 12A).

Although this form of output pares down the traces for individual sensors considerably, it actually provides a very relevant assessment of the accuracy of the static noise front estimation which was at the heart of the Astokh 4D survey mitigation strategy. Because such estimation is effectively based on mapping the envelope of the shoreward broadside maxima from a large number of model runs along a survey line, it is the performance of the model near CPA that chiefly dictates the footprint accuracy. This argument would be flawed if the shoreward noise front envelope were significantly affected by off-broadside pulses, but the consistent roll-off of pulse levels off CPA that was verified in field monitoring dispels that objection. From visual comparison of the measured pulse levels and model estimates in the several runs presented in Figure 8 it can be concluded that the 153 dB SEL sound front maps based on the noise case selections made in the course of the survey would have been largely accurate, and indeed often precautionary for the more shoreward lines of the group.

Special attention should be paid to the levels for line 13 (also known as 12A in an alternative labelling scheme used operationally during the survey), shown in the bottom right frame of Figure 8. This seismic line is almost collinear with line 12 though acquired in the opposite direction, from north to south (and with southward shifted endpoints); yet line 12 and its western neighbours had significant “A” components as shown in Figure 4 whereas line 13 was found to be a pure “B” line based on its selected noise case. This was borne out by measurements: the pulse levels for line 12 (bottom centre frame) edged tangibly above 156 dB SEL in the latter part of the run starting around past KP 11km, whereas those for line 13 – sailed on a reciprocal heading – only grazed the threshold at the crests of a few oscillations near the start of the run. Incidentally, the same oscillatory pattern characterized the pulse levels traces from AUAR 3 for both lines at equivalent source locations: around KP 14km along line 12 and KP 2km along line 13. This fact identifies the cause of the pattern to be most likely some localized ridging of the seafloor in the vicinity of the AUAR 3 receiver.

6. Preliminary discussion of the variability of noise cases

In the end the outcome of the field selection of noise cases, although clearly essential to ensure the use of the most appropriate noise footprint maps in the observational monitoring and mitigation plan, did not alter the null hypothesis going into the operation: that lines 01 through 12 would have “A” components and lines 13 to 35 would be pure “B” lines. In other words, the variations from the base case for lines susceptible to being reclassified (those in the proximity of the original demarcation) were small enough not to tip the scales. In a sense this is a strong vindication of the accuracy of the assumptions that went into the extensive preparatory modelling; still the matter of the change in noise case selection at virtually every new line was a major font of discussion among project stakeholders and advisors in the course of the survey and remains an issue in need of explanation.

Part of the reason for the perplexity over what appeared to be a vacillation between different propagation regimes was the naming used for the noise cases, such as “low plus 2” or “high minus 2”, which conveyed an inappropriate sense of fundamental difference. The three propagation modelling regimes are indeed distinct in that they provide different sound loss gradients and thus could be optimally selected on the basis of start-of-line readings at three sensors, but their level estimations largely overlap within the bounds of the applicable dB offsets. The 156 dB SEL static footprint for a given line would have somewhat different boundaries for the two cases mentioned, but the overall “reach” would be similar and indeed not unlike that of a “base plus 1” case. This approximate equivalence principle (low+1 ~ base+0 ~ high-3) does in fact allow a linear ranking of the noise cases that simplifies the analysis of their spatial or temporal distribution throughout the survey. Figure 9 shows the selected noise cases for all survey lines, converted to a base-referenced equivalent offset through the relationship above and plotted against the chronology of the line starts. This very preliminary analysis does provide empirical evidence that temporal variability of propagation parameters may be at least a contributing cause of the observed behaviour. Over the period of 20-21 June, during which little seismic survey activity took place because of often limited visibility conditions in fog, a marked transition from a more strongly propagating acoustic environment to a more acoustically lossy one appears to have taken place. Whereas before that interval the noise case selections consistently yielded +3 dB or greater equivalent offset from base, afterward they hovered between 0 dB and +2 dB equivalent offset with the majority being at +1 dB from base and two instances reaching a minimum of -1 dB (one of them being line 08 discussed earlier). The hydrological studies performed by POI during the seismic survey [2], already mentioned in this report, have revealed in post-processing the occurrence of strong temporal changes in the temperature and salinity of the water column in the area with consequent

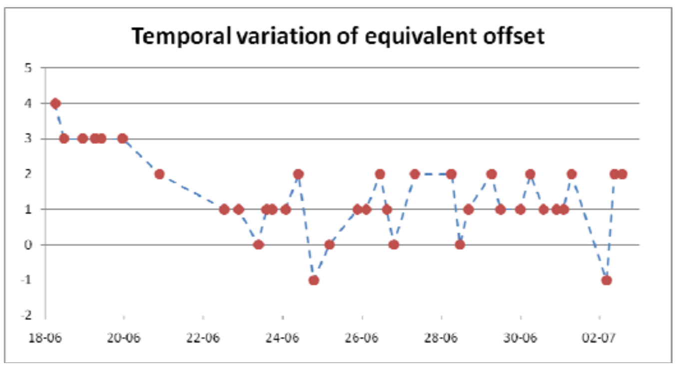


Figure 9 - Plot of base-referenced equivalent offset for all noise cases in survey versus line start chronology.

variability in the sound speed profile. From a preliminary examination of the POI results it would appear that significant and rapid changes in the underwater sound propagation properties of the area would be quite possible. No attempt has been made as of this writing to look for temporal correlation between the hydrological changes and the observed variability in noise cases or determine whether the former would by themselves thoroughly explain the latter. This remains an open field for further investigation.

References

[1] Report of the 4-D Seismic Survey Task Force at its 5th meeting (April 2010) http://cmsdata.iucn.org/downloads/wgwap_5th_seismic_survey_task_force_meeting_report.pdf

[2] Pacific Oceanological Institute, FEBRAS: Report on acoustic and hydrological studies conducted during the 2010 Sakhalin Energy Astokh 4D seismic survey (not final title; technical report for Sakhalin Energy, currently under review in preliminary version)

APPENDIX A Historical Revision Change Details

(For previous revisions)

Rev	Location of Change	Brief Description of Change
01		Approved for Use