SEISMIC SURVEYS IN COMPLEX ENVIRONMENTS: EFFECTS OF ENVIRONMENTAL VARIABILITY ON SOUND PROPAGATION AND MITIGATION PRACTICE

Ph Blondel University of Bath, Bath, UK
G Jimenez University of Bath, Bath, UK and Seiche Ltd., Bradworthy, UK
R Wyatt Seiche Ltd., Bradworthy, UK

1 INTRODUCTION

Seismic surveys are integral to the exploration of the seabed, primarily for oil and gas, but also to understand large-scale geology (e.g. fault systems or tectonic plate evolution) and to identify potential geo-hazards. There are many types of seismic surveys, based on their objectives (mapping deep hydrocarbon reservoirs or understanding sub-surface geophysics), on the types and numbers of sources used, on their durations (hours to months, depending on the areas and sub-seabed volumes to map) and on their specific environments (from deep seas to shallow waters). Acoustic sources are generally loud, and it is essential to quantify how far they are received, to monitor their potential impacts. The conclusions derived from early deep water studies cannot be directly translated to the increasingly shallow and complex environments favoured today by seismic exploration, leading to a “knowledge gap”[1]. The variability of geoacoustic seabed parameters, as one moves from the continental break to the shelf to complex near-shore geology, is compounded by the high variability of environmental parameters, as water density, salinity and temperature change with geographic location and time, at scales from hours to days. This is a problem increasingly faced by industry and academic research, as summarised in the conclusions from Oceanoise-2015[2], and one of the recommendations was the use of dynamic maps of noise impacts. But what are the best places and times to measure sound? What are the constraints on acoustic propagation? In the case of seismic surveys, what are the implications on mitigation practice?

This paper will address these different questions. The main types of seismic surveys and mitigation practices are presented in Section 2, along with the new environments in which they are increasingly used. Section 3 summarises the methodology for Sound Source Verification[3,4]. Practical implications are shown in Section 4, comparing sound propagation scenarios with field data. Factors contributing to definition of mitigation zones are explained in Section 5, highlighting the key parameters to measure in the field, and their effects on sound maps. Potential implications for data acquisition and dynamic sound mapping are discussed in Section 6 (“Conclusion”).

2 SEISMIC SURVEYS IN COMPLEX ENVIRONMENTS

2.1 Main Characteristics of Seismic Surveys

Seismic surveys can be divided into 4 modes of operation: towed streamer, ocean bottom seismics, shallow-water/transition zone and vertical seismic profiling. The former is the most common: a survey vessel tows the source and a separate acquisition cable (streamer), at a constant speed of 4-5 knots. Successive lines (3-6 hours typically) result in 2-D stratigraphic slices of the sub-seabed. A representative sailing distance of 1,000 km overall would cover an area of about 300 km^2. Larger surveys, with a typical 7,000 km sailing distance, would correspond to areas about 1,000 – 3,000 km^2 on the seabed. These numbers are illustrative of the potential variations in environmental conditions (over hours or days) and seabed properties (over these large areas). Ocean bottom seismics (OBS) uses receivers on the seabed, but their reduced operational efficiency means they are primarily used during production and monitoring, and not in exploration. Shallow-water operations also use seabed nodes, and they are made more challenging by the large tidal ranges and potentially rough surf conditions. Finally, vertical seismic profiling uses geophones lowered into well holes, down to 2 km deep, but it still uses external acoustic sources.

These seismic sources work by releasing compressed air very rapidly into the water[5]. Their relevant operating parameters are the volumes (typically from 20 to 800 in^3) and pressures (typically 2,000 psi) (the use of non-SI units corresponds to industry nomenclature). They produce short sounds at frequencies up to several kHz, every 10-15 seconds. Acoustic sources with higher operating volumes and pressures are available, producing lower frequencies. Regularly, these energy sources are used in clusters, or arrays, to increase power and minimise air bubble oscillations. Several groups of 6-8 aligned sources (called strings) result in total volumes of 3,000 – 8,000 in^3. Peak-to-peak amplitudes measured vertically, along the intended direction of maximum sound, are in the 10-100 bar-m range (i.e. 240 – 260 dB re 1 μPa @ 1 m). Pressure levels measured horizontally are 15 – 24 dB lower, and affected by the horizontal arrangement of the sources, the dimensions of the overall array, the sequential firing procedures and the proximity of the array to the water surface.

Studies of the effects of sound on marine mammals have shown higher levels cause temporal or permanent hearing loss, auditory masking, and behavioural effects and stress[6]. This increasing awareness has contributed to make sound an important part of the environmental impact assessment, and strategies to mitigate these effects have been put in place. For seismic surveys in particular, many nations have developed their own guidelines after the first guideline for the mitigation of sound produced by seismic operations, published by the Joint Nature Conservation Committee in 1995[7]. *Operational mitigation* aims to minimise the acoustic output of the source, preceding surveys with a “soft start”, or ramp up of sound levels over specific periods. *Time and area restrictions* prevent seismic surveying from specific areas and periods where significant numbers of animals are expected. Finally, *real-time monitoring* ensures that marine animals are not exposed to potentially harmful sound levels[8,9]. A safety area or *mitigation zone* around the acoustic source is defined previous to the survey and monitored in real time using visual techniques such as Marine Mammal Observers (MMOs), Protected Species Observers (PSOs), HD/thermal imaging cameras and/or acoustic methods - Passive Acoustic Monitoring, (PAM) so that survey acquisition can be temporarily stopped if animals are detected within the mitigation range. Current guidelines, country-specific, share the same general approach, but differ in some critical points such as the methodology used to define the mitigation zone[10]. Some countries establish a fixed size for the mitigation zone, whereas others define a threshold level that must not be exceeded. The latter approach, being evidence-based, is perceived as more rigorous. It is also a better way to account for variations between sound levels transmitted vertically down (and used to calibrate seismic sources) and sound levels transmitted in over directions, in particular horizontally.

2.2 Acoustically Complex Environments

2.2.1 Variations in the water column

The propagation of acoustic waves from their source spreads their energy over increasingly larger wavefronts. This geometric spreading loss is compounded by absorption losses[11]. The model of Francois-Garrison (1982)[11] determines absorption as a function of the acoustic frequency, the salinity, temperature and density (hydrostatic pressure) of the water through which it propagates. The last three parameters also affect the sound velocity, and they can vary significantly depending on the regions surveyed, their depths and the time of day or season (e.g. winter vs. summer). Sound velocity varies by ca. 0.05% when considered near the surface, 0.01% at 1 km deep and almost nothing deeper down. These small variations can still yield significant differences over large ranges. As seismic surveys move toward shallower waters, and more variable environments, they are increasingly confronted with variations near the sea surface, from solar irradiance and wind velocities. Near the equator, the sea surface is generally warmer and winds are light. Tropical waters have lower temperatures and strong winds. Higher latitudes show decreasing temperatures at the sea surface and small to strong winds. Wind contributes to surface water evaporation, affecting local salinity, and it causes downward mixing of surface water, generally warmer, with deeper water, generally colder. Close to shores, freshwater influx from rivers and mid-water currents can drastically change the local salinity. In polar and high-latitude regions, this can also vary during the day, for example with ice melting with sunshine and adding fresh water.

At frequencies above 10 Hz, the acoustic wavelengths become comparable to the scale of potential irregularities on the sea surface or seabed. Most of the seismic energy is directed downward, but a significant portion is still transmitted in other directions, e.g. horizontally. In shallow waters, multi-path propagation will become important, especially at larger ranges[11]. Any variations in the water column properties will therefore be amplified by these longer propagation ranges, and affected by seabed reflections at different angles.

2.2.2 Variations of the seafloor

Continental margins are varied in morphology and in geology (Figure 1). It has been estimated that as much as 90% of sediments generated by land erosion are deposited there, particular in major deltas. This results in large-scale sedimentary structures, such as estuaries, deltas and fans. A large portion of the accumulated sediment then moves further downslope, transported through large debris slides, or along narrow channels merging into submarine canyons.

Sound propagating from seismic sources will be greatly affected by the differences in morphology and depth. Acoustic propagation downslope will be affected by geometric spreading toward deeper waters, reducing measured sound levels. The increasing homogenization of seabed types (e.g. toward the abyssal plains) will decrease the overall variation between sound levels measured at comparable ranges, but in slightly different directions, better reflecting the horizontal directivity of the sources as measured during initial calibration or modelling. Conversely, sound propagating upslope will be affected by decreasing depths and increasing probabilities of multiple reflections, generally increasing sound levels. Measurements at similar ranges from the source(s) but at different angles will be strongly affected by the line-of-sight variations of seabed topography, at scales comparable to the acoustic wavelengths considered. The local seabed geology will also affect the scattering from acoustic waves (depending on local slopes and roughness).

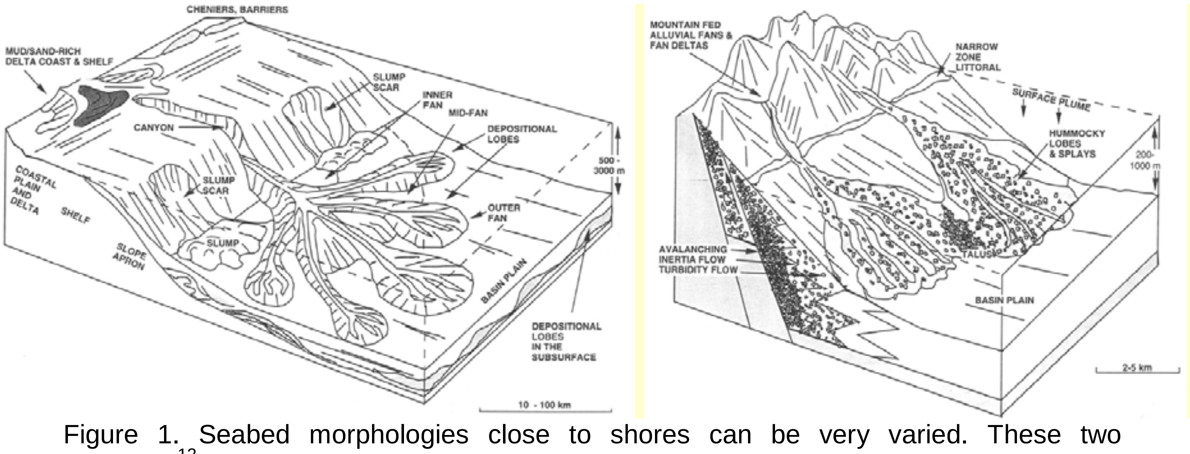

Figure 1. Seabed morphologies close to shores can be very varied. These two examples[12] show a typical point-source, mud/sand rich submarine fan (left) and a multiple-source, gravel-rich ramp (right). The exact geological descriptions are site-specific but the seabed shapes are typical. The morphological variations close to shore and their respective spatial scales (10 – 100 km, left, compared with 2 – 5 km, right) hint to the challenges in measuring and modelling acoustic propagation from moving seismic sources.

2.2.3 Acoustic Variability

The acoustic variability is illustrated in Figure 2 (Jimenez et al., unpublished, 2014). Sound levels were measured by a support vessel, sailing at 3 - 6 knots and at ranges 4 – 7 km in front of the seismic vessel, at azimuthal angles 20° – 40° from the lines surveyed. These measurements were acquired in tropical water depths of 1 – 2 km, over a total area of 10,000 km^2. The source levels were kept constant, and matched the modelled sound level for the seismic array in use. The physical layout between source and receiver was also kept relatively constant, with similar and stable bearings and similar ranges. The sound levels show a rather large spread, up to 20 dB. Based on observations and subsequent modelling, this spread is attributed to variations in the water column (radiative forcing in the upper layers and changes in weather conditions and sea states) and in seafloor morphology and geology.

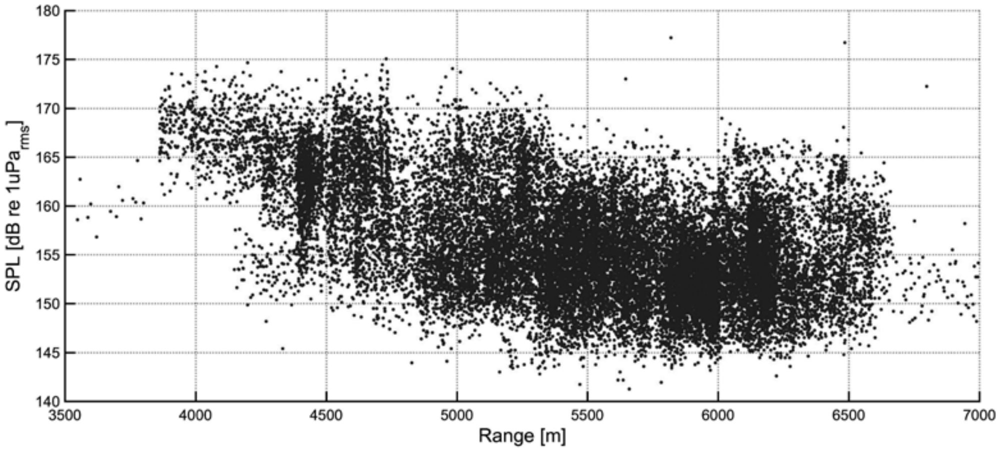

Figure 2. Variations in sound levels measured at different ranges from a seismic source moving in water depths of 1 to 2 km. The spread (up to 20 dB) is attributed to propagation effects and the physical properties of the environment (water layer and seabed). From Jimenez et al. (confidential commercial report, 2014). Reproduced with permission.

3 SOUND SOURCE VERIFICATION (SSV)

Sound levels measured in complex environments, such as those presented in Figure 3, show a large spread if not presented in their wider context, i.e. with ranges/bearings from the source(s) and line-of-sight variations of the underlying seafloor. It is also difficult to translate these measurements into recommended mitigation ranges if the 3-D directivity of the source(s) is not taken into account. Sound Source Verification[3,4] (SSV) is used to estimate mitigation zones based on measurements and models of the sound field and specific threshold levels, based on mitigation values (Figure 3).

The acoustic signature of seismic sources, alone or in clusters, can be accurately predicted due to the relative simplicity of the physical principles and a wealth of validation studies[13]. The following examples are taken from a commercial survey undertaken in shallow, coastal waters of the North Pacific. The high-power seismic source consisted in two strings of three pairs of clustered acoustic sources. The time and frequency responses of its far-field signature were modelled for the endfire and broadside directions, and normalised to a reference distance of 1 m. The signatures include source interactions and reflections in upper and lower water boundaries. They are generated for a grazing angle of 20° well correlated with the acoustic energy measured in the water column. Most of the sound is project downwards and nearly vertical directions vanish within the seabed[13]. The effect of the first surface (ghost) reflection is neglected in first instance.

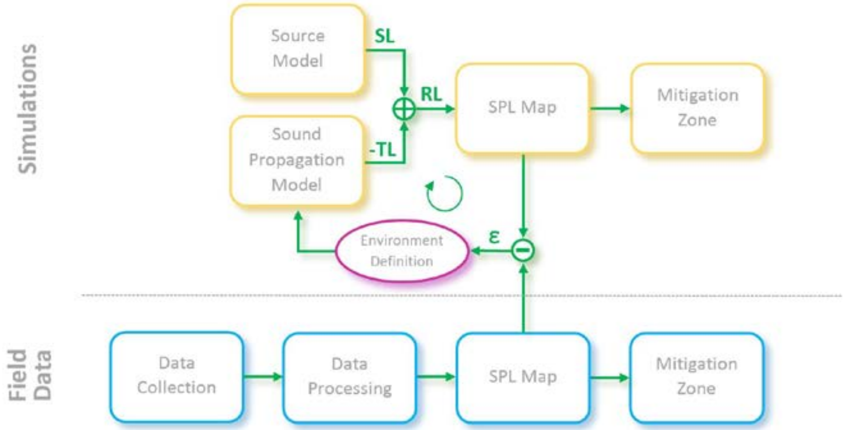

Figure 3. Stages of Sound Source Verification (SSV), used to estimate mitigation zones based on measurements and models of the sound field and specific threshold levels

Propagation losses are calculated using the range-dependent Parabolic Equation model RAMGeo[14] **(**for fluid sediments. Sound velocities in the water column are practically constant for the times at which measurements were made. The general area of this survey is a tidal bay near glaciers. Surface sediments are mainly clay and siliceous mud. High tidal currents and marine deposition created sand waves and megaripples (first 25 m below the seabed). Various glacial units are emplaced 25 – 75 m below the surface. Shallow slopes and basins change the topography of the south-central part of the bay. For modelling, the acoustic properties of these different layers are taken from compiled values[15]. Central frequencies of 31.25 Hz, 62.5 Hz, 125 Hz, 250 Hz, 500 Hz and 1 kHz have been used. Transmission losses were simulated over 18 vertical transect planes evenly spaced by 20°, each 10 km long. The received Sound Exposure Levels were calculated by subtracting them from the band source levels modelled for the seismic source. A 2-D horizontal map is then generated at the selected depth of the receiver, applying linear circular interpolation between transects. The 24-hour cumulative SEL map is then calculated from the single-shot values.

SSV often uses trials prior to the survey to validate/refine these simulations, better defining the potential mitigation zones. In this case, the seismic source was fixed, 3 m deep and transmitting every 30 seconds. Six drifting buoys were deployed upstream to measure sound levels 2 m deep. The strong currents during the tidal cycle allowed them to cover distances of up to 20 km (over a total time of 7 hours, including 30 minutes for deployment from a small vessel and 30 minutes for recovery of each buoy). Very shallow (2 – 10 m) and shallow (10 – 50 m) depths were investigated, with three array configurations. Models and measurements are compared in the next two sections.

4 ENVIRONMENTAL VARIABILITY AND THE SOUND FIELD

Figure 4 (top) compares the bathymetry from two different parts of the bay, shallow and very shallow. In the preliminary trials, the seismic source is fixed. Measured SELs (acquired along the drift buoy tracks, outlined in black) are interpolated over a 10 km range from the source (Figure 4, bottom). These SELs, cumulated over 24 hours, assume that marine mammals remain static during this period; this is of course exaggerated and overestimates potential mitigation scenarios.

Sound levels decrease with range, as expected, but drift-buoy measurements have shown fluctuations of the order of 5 dB over small sections (a few hundred meters to 1 km). Every so often, very low pulses are recorded, with levels 15 – 20 dB lower. It is worth clarifying that the general detection of acoustic pulses is automated, but each detection was manually verified by visual and auditory inspection, and any spurious pulse removed. These low-level pulses are characterized by a minimum high frequency content, and may result from shadowing effects within the water column. SELs in deeper water are, as a whole, about 10 dB higher than in the very shallow region. Most of the energy content of the seismic sources is below 250 Hz; at these frequencies, the wavelength is

> 6 m, thus comparable to predominant depths (5-15 m). Bandpass filtering of the acoustic energy for the octave bands of 62.5 Hz, 250 Hz and 1 kHz (not shown for lack of space) shows that water depth hinders the propagation of the lower frequencies. At 1 kHz, the seabed becomes a hard reflector, the water depth is large enough compared to the pulse wavelength (10 m vs 1.5 m), and absorption in water is almost negligible. SELs are about 10 dB lower at 1 kHz compared to those at 250 Hz, not a large difference bearing in mind that the band levels differ by almost 20 dB. In short, the high-pass filter response of the environment results in an overall flattening of the low frequency response of the source. Consequently, sound levels in shallow waters are more evenly distributed through the spectra than in deeper waters.

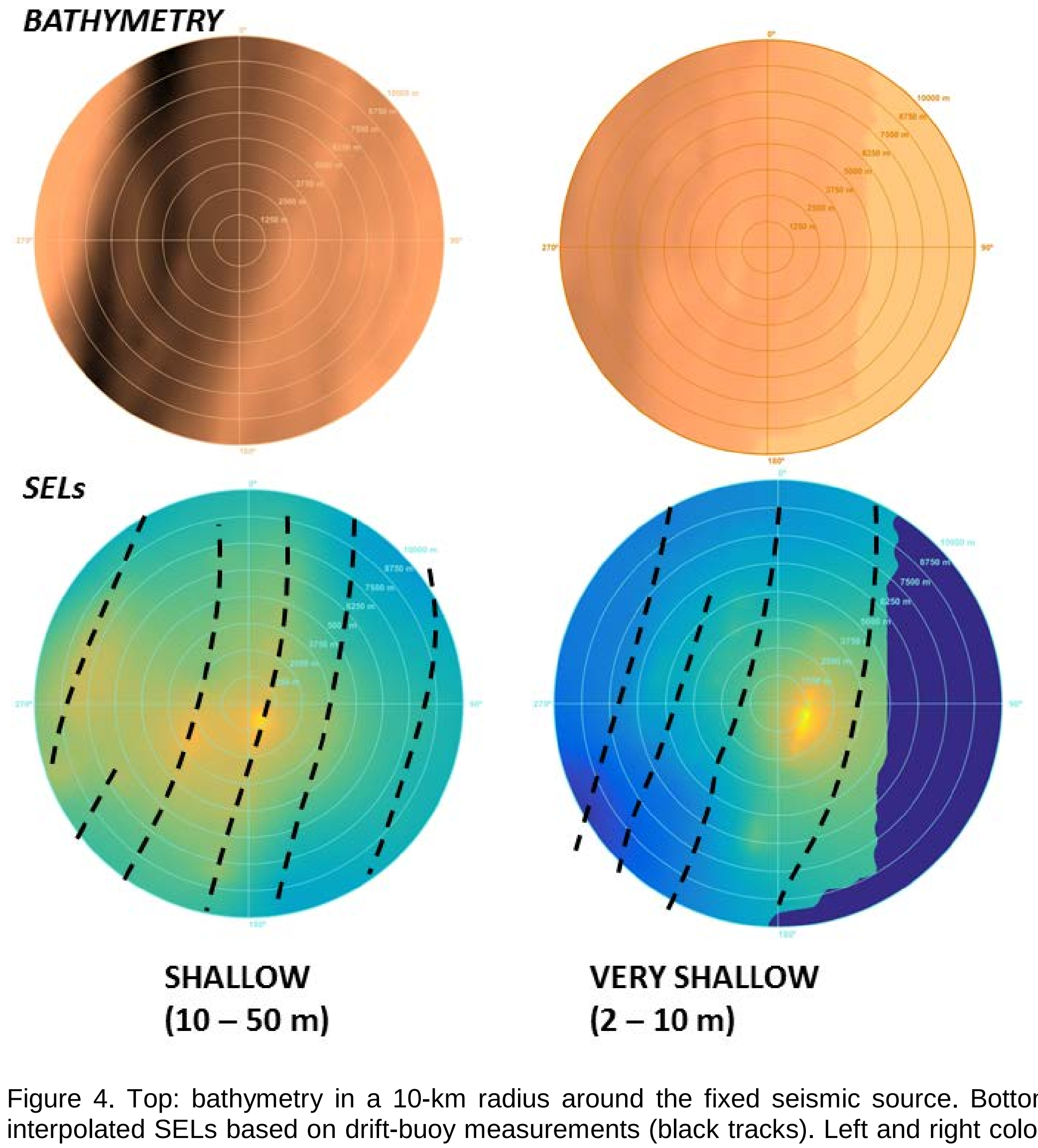

Figure 4. Top: bathymetry in a 10-km radius around the fixed seismic source. Bottom: interpolated SELs based on drift-buoy measurements (black tracks). Left and right colour scales encompass the same ranges of depths (top) and energy levels (bottom).

5 FACTORS CONTRIBUTING TO THE SIZE OF MITIGATION ZONES

Mitigation zones are defined differently according to countries and regulators, with some recommending a fixed range and others looking at threshold levels for marine mammal species of interest. We use here the revised NOAA Guidelines[16], based on the latest scientific information about animal hearing and strongly measurement-based. Figure 5 (top left) shows the reference scenario, with a source 3 m deep, firing every 30 s (i.e. 2,880 pulses in 24 h). The mitigation zone (highlighted in red) is based on measurements and suited to a minke whale (sensitive to lower frequencies). It is asymmetric and larger westward, pointing toward areas deeper but with increasing slopes. Figure 5 (top, middle) moves the source to shallower water: the mitigation range is nearly halved (average of 4,636 m decreasing to 2,728 m) and becomes nearly circular. The effect of bathymetry (and slopes facing toward or away from the seismic source) is therefore particularly large. Figure 5 (top right) now considers a different cetacean (beluga whale, sensitive to middle frequencies). The average mitigation range now reduces to 6 m; this is less surprising than thought as the energy of the seismic array is concentrated below 250 Hz, where the auditory response of the beluga attenuates by more than 50 dB. The hearing sensitivity of the animals is therefore particular important, and the mitigation strategy needs to fully consider the likely species. Figure 5 (bottom left) shows what happens as the animal (a minke whale, again) now moves closer to the surface (1 m). Sound levels decrease by 6 – 8 dB and the average mitigation range is halved (2,445 m). This is attributed to cancellation of the direct signal by its surface reflection, of same amplitude and inverted phase. The depth of the source can also vary, either for operational reasons or because of sea state. Figure 5 (bottom, middle) shows slightly lower SELs, resulting in a more circular mitigation zone of 3,590 m radius. This can be explained by the effect of the ghost reflection, which generates a frequency comb filter in frequency. The closer the source is to the surface, the higher the low frequency attenuation, since the major energy content of the array is in the low end of the spectra, the reduction in source depth results in a decreased broadband level. Finally, Figure 5 (bottom right) shows the effect on cumulative SELs of doubling the number of shots per hour, from 120 to 240. This leads to a global 3-dB increase and higher mitigation ranges of 5,795 m in average, with westward asymmetry like the reference scenario, larger north-westward.

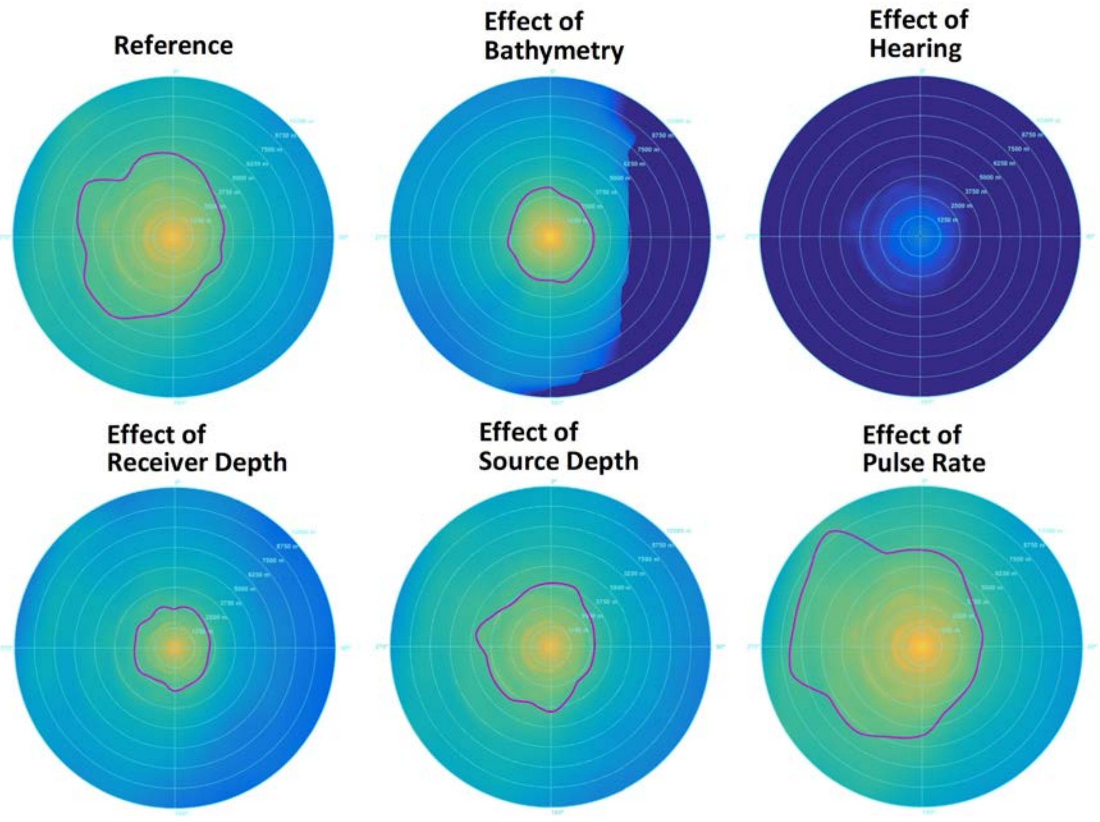

Figure 5. Variations of SELs and mitigation zones with different scenarios (see text for details).

These differences are important to mitigation efforts, but they would not have been picked up just from measurements, as some variations could not have been tested in the trial phase. Using Sound Source Verification, it is however possible to quantify the effects on the sizes and shapes of the mitigation zones from variations in bathymetry (depths and slopes), hearing sensitivity of the animals to be protected, their depths in water (for example if diving or moving), the depths of the seismic sources in water (e.g. for clusters) and their firing rates.

Acknowledgments: This work is supported by Innovate UK (Knowledge Transfer Partnership grant # KTP009203). The cooperative spirit of the partners whose data is presented here is gratefully acknowledged.

6 REFERENCES

1. D. Hedgeland, M. Jenkerson, R, Abma, C. Correa, S. Hayes, I. Lambert, J. Norton and N. Robinson, Report of Seismic Survey Session, Oceanoise2015, Vilanova i la Geltrú (2015).
2. C. Erbe, T. Folegot, F. Aulanier, B. Binnerts, G. Jiménez, D. Risch and L. Simon. Report of the Mapping and Modelling Session, Oceanoise2015, Vilanova i la Geltrú, (2015).
3. B. Heath and R. Wyatt; ‘Sound Source Verification to assess marine mammal impact’; Sea Technology 55(12):47-50 (December 2014)
4. Jimenez, G., Ph. Blondel, B. Heath and R. Wyatt. Seismic Surveys in Complex Environments – Analysing the Variability of Exclusion Zones with Field Measurements and Models. Proc. 4th Int. Conference on the Effects of Noise on Aquatic Life, Dublin (2016).
5. W.A. Telford, L.P. Geldart and R.E. Sheriff RE. Applied Geophysics, 2nd ed. Cambridge University Press (1990).
6. B.L. Southall, A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene Jr, D. Kastak, D.R. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas and P.L. Tyack. Marine Mammal Noise-Exposure Criteria: Initial Scientific Recommendations, Bioacoustics 17(1-3):273-275 (2008).
7. Joint Nature Conservation Committee (JNCC). JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys, Joint Nature Conservation Committee, Aberdeen, 2010.
8. R. Compton, L. Goodwin; R. Handy, V. Abbot, ‘A critical examination of the worldwide guideline for minimising the disturbance to marine mammals during seismic surveys’, Marine Policy 32(3): 255-262 (2008).
9. C. Weir and S. Dolman, ‘Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard’, J. Int. Wildlife Law and Policy 10:1-27 (2007).
10. C. Erbe, “International regulation of underwater noise”, Acous. Aust. 41(1):12-19 (2013).
11. X. Lurton. An Introduction to Underwater Acoustics: Principles and Applications, 2nd ed. Springer Praxis (2010).
12. H.G. Reading and M. Richards; ‘Turbidite systems in deep-water basin margins classified by grain size and feeder system’, AAPG Bull. 78(5):792-822 (1994).
13. M.A. Ainslie, M.B. Halvorsen and R. Dekeling . International Airgun Modelling Workshop: Validation of Source Signature and Sound Propagation Models. Proc. 4th Int. Conference on the Effects of Noise on Aquatic Life, Dublin (2016).
14. M.D. Collins, R.J. Cederberg, D.B. King and S.A. Chin-Bing, 1996, ‘Comparison of algorithms for solving parabolic wave equations’. J. Acoust. Soc. Am. 100(1):178-182 (1996).
15. E. Hamilton, ‘Geoacoustic modeling of the sea floor’, J. Acoust. Soc. Am. 68(5):313:1340 (1980)
16. NOAA, ‘Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing - Underwater acoustic threshold for onset of permanent and temporary threshold shifts’, NOAA Tech. Memo. NMFS-OPR-55 (2016)