# Transmission of marine seismic survey, air gun array signals in Australian waters.

**Robert D. McCauley[1], Alec J. Duncan[1], Alexander N. Gavrilov[1], Douglas H. Cato[2]**

[1]Centre Marine Science and Technology Curtin University, Perth Western Australia
[2]Defence Science and Technology Group and School of Geosciences, University of Sydney, Australia

## ABSTRACT

Measurements of the transmission of seismic survey signals in Australian waters are presented. The measured transmission loss showed: high variability of received signal sound exposure level at similar ranges when comparing all surveys (mean of standard deviation across ranges of 3-12 dB); high variability within a seismic survey (mean of standard deviation at any range of 2-4 dB); typical shot-shot variability of 1-3 dB (mean of standard deviation at any range) possibly produced by gun strings moving around; the importance of bathymetry profiles, seabed types and sound speed profiles in determining air gun transmission; different transmission regimes for open ocean, continental shelf and shelf-slope environments; seismic source energy transmitted at longer ranges (> 1 km) was most commonly dominated by low frequency (< 500 Hz) energy and only at short range (< 1 km) was high frequency energy observed; and that a considerable amount of air gun array energy may directly excite the seabed, couple into the seabed and travel horizontally, or by way of interface waves. For locations on the shelf or shelf slope around southern and western Australia the presence of limestone or calcarenite seabed types are critical in accurately determining seismic signal transmission.

## 1. INTRODUCTION

Marine petroleum seismic surveys (“seismic” hereafter) involve the repetitive use of impulsive sound sources to generate downward focused, low-frequency sound energy for reflective imaging of sub-sea geological structures. This is the primary technique used to locate sub-sea petroleum deposits as well as being used for scientific studies of the earth's crust or engineering studies of relatively shallow sediments. The primary sound sources used are currently air guns, which operate by rapidly releasing compressed air into the water column in a controlled fashion. Typically many air guns are configured into arrays, which are towed at 5-8 m depth below the sea surface and are synchronously operated at time intervals set by the desired horizontal spacing between signals and the tow vessel's speed. Surveys in continental shelf waters will operate at a 6-10 s repetition rate, while surveys run over shelf slope or in full ocean depths must operate at longer time intervals to allow a sufficient period for the sub-sea reflections to travel the extra distance through the water column.

The seismic industry operates under considerable environmental scrutiny, given that the sound sources used can be considered intense and may be used for long periods in localised regions. Seismic survey operations often involve environmental mitigation measures, such as seasonal region closures to surveys or operational procedures to detect large marine fauna and power down if fauna come within some pre-determined range. Some seismic survey environmental mitigation measures allow for modifications in shut down range based on "threshold levels" combined with modelling transmission of the seismic source.

The transmission loss curves of marine seismic noise with range in differing environments have been previously reported in the northern hemisphere by Malme et al (1986) who modeled and summarised measurements of single and multiple air gun transmission in Californian waters, Greene & Richardson (1988) who describe sound transmission from four seismic surveys in the Beaufort Sea and Tashmukhambetov et al. (2008) who measured a 3D array in deep water. Several authors report on long range (1000’s km) detection of marine seismic signals in the deep ocean, such as Nieukirk et al (2004). These oceanic long range detections result from deep ocean sound channel ducting or convergence phenomena. While ducting in the deep sound channel may be common for sources operating in deep water or over the continental slope, such ducting would not occur for sources operating on the continental shelf.

Since 2000, Australian petroleum companies have been funding sea noise logger deployments in the vicinity of seismic survey operations. This has enabled the establishment of a library of Australian air gun array signals at Curtin University and the decay of these signals with range from the source. By combining the received air gun signals with appropriate seismic navigational data, source details and environmental parameters, we present a short summary of phenomena associated with the transmission of air gun signals in Australian waters and so provide some confidence and baseline information for predicting the transmission of seismic signals, plus highlight that the transmission of signals from seismic sources is not simple nor necessarily consistent. There are numerous sound transmission phenomena seen in the seismic records, some of these are displayed but not explored in detail here. The factors influencing transmission of seismic signals apply to environmental assessments of how seismic signals may impact marine fauna.

## 2. METHODS

### 2.1 Recording equipment and configuration

Air gun signals have been recorded with four different sound recorders, DAT tape decks or three types of sea noise loggers, as defined in Table 1, Appendix 1. Each sea noise recording (hydrophone in and out the water) has been designated a set number which is used through this document. Except for the DAT tape deck records and the Sedis IV loggers (GeoPro GmbH) which ran continuously, there were many samples associated with a set, where sea noise loggers sampled at a duty cycle.

The CMST-DSTO sea noise logger design comprised an external hydrophone connected to: an impedance matching pre-amplifier with -20 to 20 dB gain (modified RANRL PA6511-A high impedance, low noise); signal conditioning card (a high pass filter with low frequency roll-off to flatten naturally high levels of low frequency noise below 10 Hz, anti-aliasing filters and further programmable 0 to 20 dB gain); a 16-bit A-D card (0 to 5 V nominal range, clipping occurred at 4.96 V); a sampling processor which wrote digitised samples at prescribed and flexible sampling regimes to a flash card as discrete files; and one or several 3.5" hard disks which the data on the flash card was periodically dumped to. At the recording end sea noise files from the flash card and hard disk were consolidated onto a single PC hard disk, backed up and were available for analysis. This logger was fully programmable in sample rate, sampling duty cycles (sample schedule), filters, had two options of low frequency rolloffs (starting at 8 or 160 Hz) and allowed for multiple sampling regimes using different gains, sample rates and filters. For deployments which were known in advance to involve air gun measurements the CMST-DSTO instruments were set with multiple gains, with a low gain channel for short range signals and a high gain channel for long range signals.

All systems used calibrated hydrophones (factory supplied calibration sheets). In all recordings each system's frequency and gain response was checked using white noise of known level fed into the pre-amplifier directly or, for all CMST-DSTO instruments, input in-series with the hydrophone or a capacitor of similar capacitance to the hydrophone. Calibrations were made in acoustically and electrically shielded boxes. The CMST-DSTO logger calibration technique accurately accounted for all impedance matches in the hydrophone to recording system. The system gain-response as analysed during calibration and the hydrophone sensitivity were used to convert sampled voltages into pressure units. All CMST-DSTO logger clocks were set to UTC time before deployment and the clock drift read after deployment using GPS time synchronization pulses. Sample times were then adjusted assuming a linear clock drift between time checks.

The Sedis IV instruments were deployed under contract to Santos by GeoPro GMBH staff. Specifications of the Sedis IV equipment can be found at http://sismic2.iec.cat/orfeus/instrumentation/daqs_info_sheets/geo_pro_sedis-4.pdf. The Sedis IV recorders comprised a sphere suspended in a frame anchored to the seabed by weights with a Benthos hydrophone measuring sound pressure external to and mounted on the sphere. A burn wire acoustic release was used in the Sedis IV units. The Sedis IV units included 3-axis geophones.

Except for one other instance (set 2090) in which the hydrophone was deployed drifting suspended from floats, all hydrophones and sea noise loggers were deployed on the seabed with the hydrophone lying directly on the seabed. These deployments used a weighted ground line typically twice the water depth in length to a riser with acoustic release (EdgeTech, ORE CART) and floats.

Two of the CMST-DSTO sea noise loggers were modified to include 3-axis geophone sensors to measure ground borne vibration. One sensor an ION Geophysical, SM-6/U-B 10 Hz was set in the vertical axes and two SM-6/H-B 10 Hz aligned $90^{o}$ apart in the horizontal. All sea noise logger housings were set on the seabed. The housings were stainless steel, 6 mm wall thickness and had plastic cross bars with weights at one end to prevent the housing rolling. The weight of the housing, cross bar and batteries (~ 40 kg underwater) ensured the housing was firmly coupled to the seabed.

## 2.2 Analysis of air gun signals

Analysis of air gun signals has a confusing legacy in the literature, with a variety of unit systems used. It is generally agreed that for impulsive signals a measure of a signals' energy or a measure proportional to energy is the best unit (McCauley et al 2003) although for close range biological noise impacts peak pressures may relate to potential physiological damage (ie. Halverson et al. 2012 for fish). The approach here has been to isolate air gun signals (below) and calculate a suite of measures from each signal as defined by McCauley et al. (2003). The units commonly used in this paper to characterise air gun signals are a measure proportional to the signals' total energy in units of dB re 1 $\mu Pa^2 \cdot s$ or sound exposure level (SEL), plus peak-to-peak level (dB re 1 µPa). Where rms or sound pressure level (SPL) units are presented (dB re 1 µPa) the averaging period is taken to be the time for 90% of the air gun signals' energy to pass (technique of Malme et al. 1986), which is calculated from the cumulative curve of $P^2 \cdot s$. Problems with analysing air gun signals included: 1) overlapping transients (biologics, vessels or artefacts being most common) which skewed measured levels upwards; 2) multipath propagation and reverberation of one air gun signal lagging into the following air gun signal; 3) ground borne precursor paths (often there were multiple precursors) arriving in the time period of the preceding signal; or 4) signal overloading. Problems 1) to 3) only applied to long range or weak signals (close to the respective noise threshold) while overloading only applied to shorter range signals.

As there was large variability in measured parameters of seismic signals along any given survey line and across a survey, to simplify comparisons of surveys the SEL measures with range for each data set were averaged within log scaled range bins, since sound transmission in the ocean usually approximates some form of logarithmic loss. The range bin boundaries used were as given by the 1/3 octave scale. Linear statistics of SEL in decibels were used within each range bin as opposed to statistics applied in the linear domain and these converted back to dB, since animal hearing sensitivity is approximately directly proportional to the dB scale. Within each range bin the mean level, standard deviation and 95% confidence limits of received level were calculated using all data available for the respective survey. Thus for each survey these range-averaged levels 'smooth out' horizontal angular dependence of the air gun source, small time scale differences between received shots and the peculiarities of sound transmission due to local environment differences.

Some received air gun signals were clipped even on the low gain channel. Several deployments were made where we were not aware a seismic survey would occur in the area, but were able to source navigation data after the event and so develop received level with range curves. These data sets often contained clipped signals, which were noted during analysis. While we developed a routine to estimate sound exposure levels reliably from clipped signals, only un-clipped signals have been used throughout this document.

## 2.3 Extraction of air gun signals

To retrieve air gun signals from sea noise records the following steps were taken: 1) the time of air gun firing from supplied seismic navigation data (generally p190 files) was used to bracket batches of received air gun signals in sea noise records (since not all received air gun signals had navigation data); 2) these batches were perused in sections (typically length of the sea noise logger sample) to identify any section with overlapping boats, whales or artefacts which would give false results and these samples excluded from analysis; 3) the transmit time of each signal within selected batches was used with the approximate travel time (array to receiver, derived from the horizontal range and an assumed sound speed adjusted to give the best match of transmit / arrival times) to estimate the received time of the leading edge of the waterborne arrival: 4) the predicted time of the leading edge of the waterborne arrival was bracketed to retrieve the air gun signal - the bracketing period varied using several algorithms to account for multipath reflections arriving after the predicted first waterborne arrival and to account for ground borne energy arriving before the leading edge of the first waterborne arrival (sound speeds being higher in the sediment); 5) for each batch of air gun signals, a few signals close to the minimum and maximum ranges were checked to ensure that the estimated, pre and post leading edge arrival times matched the received signals; 6) air gun signals were extracted for that batch using the high gain channel; 7) the voltage of each signal was checked and if it had clipped (exceeded a +ve value or gone below a -ve value) and a low gain channel was available, the low gain channel was loaded, a flag was set for all signals to indicate whether it had clipped or not (appropriate high or low gain channel); 8) each signal was converted into pressure units using appropriate calibration data (accounting for system gain and hydrophone sensitivity); 9) each air gun signal was then analysed for the parameters defined in McCauley et al. (2001); 10) a calibrated power spectral density was obtained for each signal; 11) for each signal navigational data of the receiver's range to array centre, transmit and receive time (waterborne leading edge as received), array tow direction at the time of firing, (compass) angle of the array tow direction to the receiver ($0^o$ = ahead, $90^o$ = abeam starboard, $180^o$ = astern), minimum and maximum water depth along the source-receiver travel path plus water depth at source and receiver (from gridded bathymetry data) and the array position were calculated; and 12) appropriate calculated data for each air gun signal was saved. The source navigation data in *.p190 file format was obtained from the respective survey company. Bathymetry was gridded from the *.p190 seismic vessels' ecohosounder data embedded in the navigation files, the Geoscience Australia bathymetry data set (Petkovic and Buchanan, 2002), bathymetry data supplied by the respective company or, usually, some combination of these.

### 2.4 Measurements made:

Forty nine sets of sound transmission data from 24 seismic sources have been included in results along with transmission sets from a 20 and 140 cui air gun used by the authors for research purposes. Commercial air gun arrays measured ranged from 1115 to 4140 cui. Locations of sites sampled are shown on Figure 1. For confidentiality reasons specific surveys cannot be identified. For each seismic source the array configuration was available (X, Y, Z, volume and operating pressure of each airgun). Only signals which had not clipped have been used throughout.

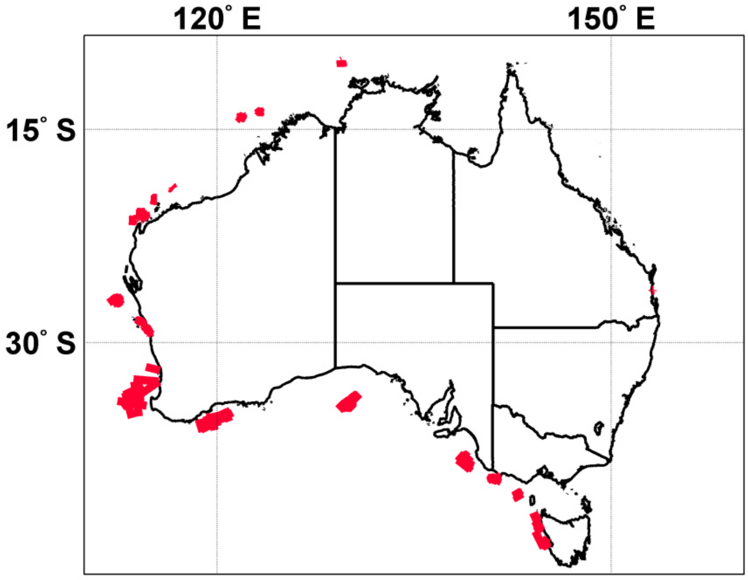


Figure 1: Location of all seismic surveys measured (red lines).

## 3. RESULTS - SEISMIC SIGNAL DECAY

To highlight the wide spread of measured levels of air gun array signals received at different ranges, the decay curves for all data sets analysed are shown on Figure 2 for peak-to-peak and SEL measures displayed by source volume, and only every 25th point displayed. It is obvious from Figure 2 that there is a very large variability in received air gun signal levels with range. To simplify interpretation the measures for individual surveys were averaged in logarithmic range bins and the mean plus the 95% confidence limit were plotted as shown for SEL and SPL on Figure 3. By using the 95th percentile in each range bin the curves encompass expected variability along track from an air gun source such that 95% of received signals will lie at or below the curve. This averaging removes the directionality patterns inherent in the spatially dispersed arrays of air guns.

To investigate signal variability Figure 4a) shows the mean of the standard deviation (s.d.) in logarithmic range bins when considering: 1) all seismic survey data lumped within each range category; 2) data from individual surveys (ie. the s.d. calculated for each survey and range bin independently, then averaged across surveys); and 3) the shot to shot variability (compares one shot with the next if they are within 20 s of each other and plots the s.d. using all data in each range bin).

In Australian waters mitigation measures are split by the estimated received level of a seismic source at 1 km range, about a 160 dB re 1µPa$^2$·s (SEL) value. Sources which produce estimated SEL levels > 160 dB re 1µPa$^2$·s at 1 km have a stricter mitigation regime than sources which produce SEL < 160 dB re 1µPa$^2$·s at 1 km. To illustrate how the measured SEL varies at 1 km by source volume, the measured SEL at 1 km range has been displayed with source volume on Figure 4 b). An example of a small seismic source emulating a larger source can be seen on Figure 4 b) for the two values of a 140 cui source producing similar received levels at 1 km to a 2000-2500 cui commercial array. This arose as the smaller source was used in experiments and designed to emulate a larger source plus have minimal directionality. The smaller source was spatially a tight cluster, with four guns spaced in a rectangle, 1.3 m wide and 1.1 m long, so the sources were acting more efficiently as a point source compared to the much larger spatial scale of a commercial air gun array. Using the commercial array source layouts an "average array" was 14 ± 0.7 m across the tow direction and 16 ± 3.3 m in the tow direction (± 95 % confidence limits).

To highlight sound transmission phenomena related to bathymetry and the measured frequency content of a seismic source, Figure 5 shows the frequency content, sound exposure level and bathymetry along a survey line which passes from offshore waters, almost directly over a receiver, then inshore across the continental shelf. To further highlight differences of the transmission of seismic signals related to environmental parameters two sources of similar sizes operating in similar water depths but over different seabed types (deep sand and thin or no sand over limestone) have been plotted on Figure 6.

Finally, the primary environmental issues relating to seismic air gun sources have considered waterborne energy only, typically for impacts on marine mammals. A considerable amount of the energy generated in the water column by a seismic source may couple into the seabed and transmit through the substrate or along the substrate boundaries. An example of the waterborne pressure and ground borne vibration at the seabed generated by a 3130 cui source operating in 40 m water depth is shown on Figure 7.

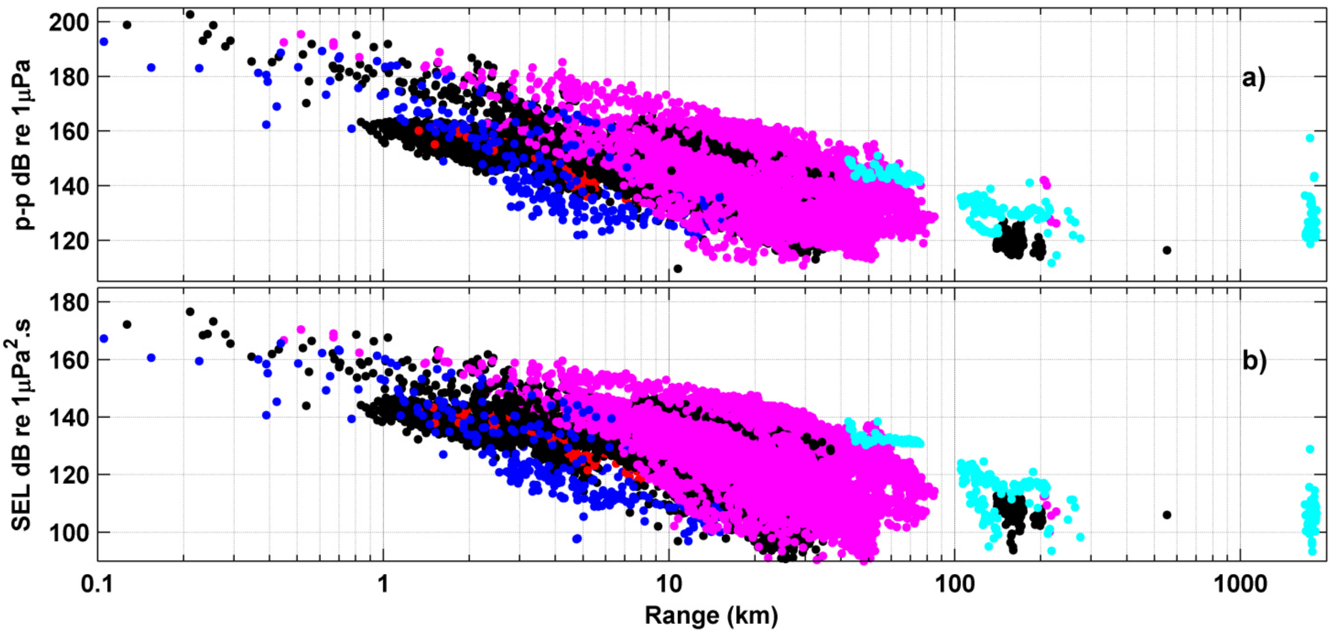


Figure 2: **Transmission decay curves** for all sets of air gun signals analysed in peak to peak (a) and SEL (b) units over ranges of 10 m to 1850 km. For clarity only every 25th air gun signal is displayed. Data sets are colour coded as: 0 to 1000 cui blue; 1000 to 2000 cui red; 2000 to 3000 cui black; 3000 to 4000 cui magenta; 4000 to 5000 cui cyan.

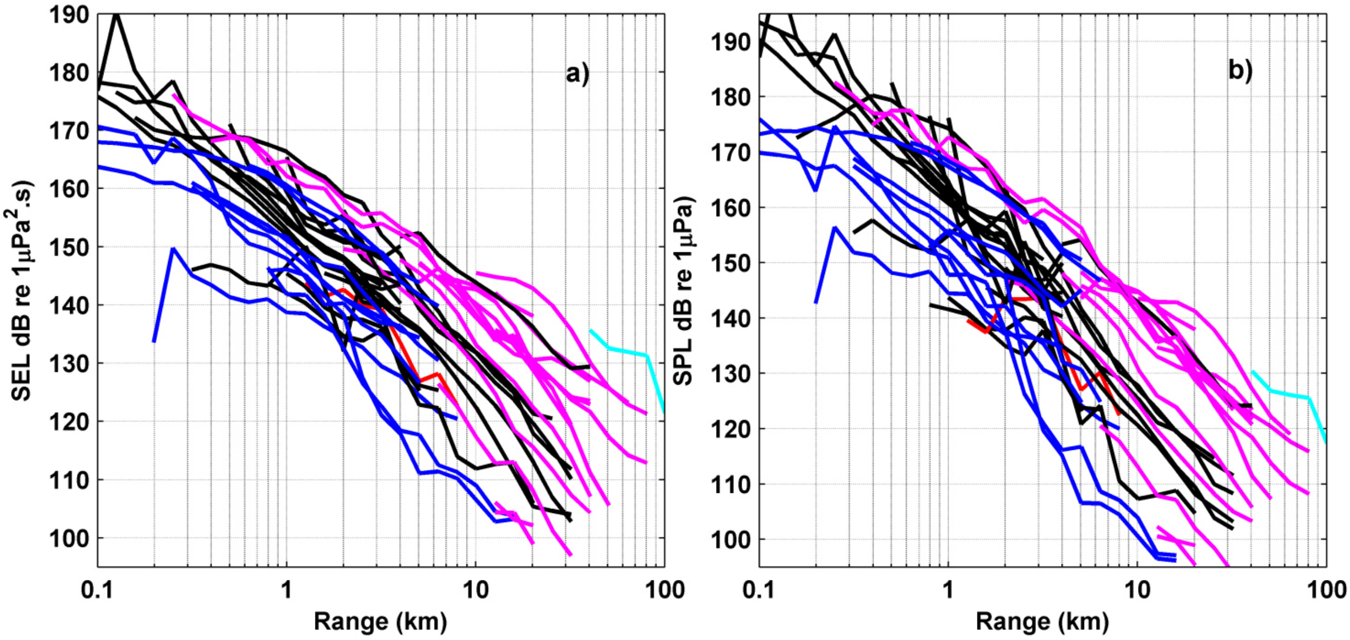


Figure 3: **95th percentile of received level** (a/ is SEL and b/ is SPL) of all seismic sources over 0.1 to 100 km within log spaced range bins. The curve colour denotes the array or gun size as per Figure 2.

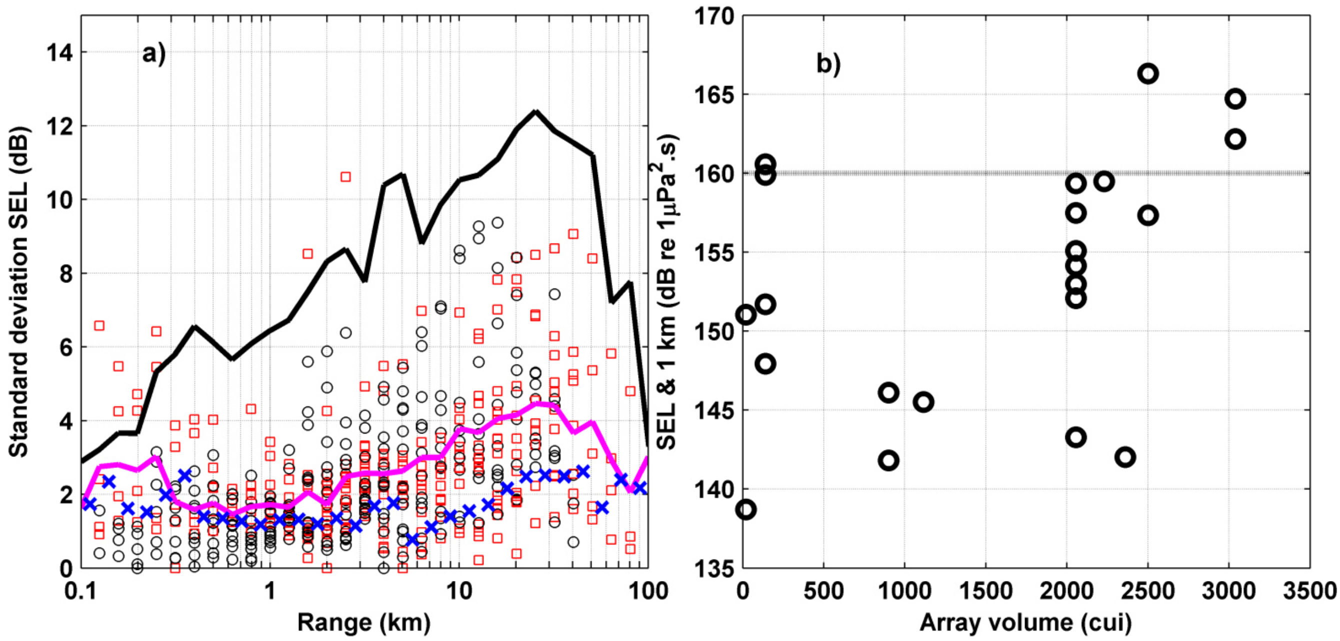


Figure 4: **Standard deviation (s.d.) of sound exposure level and array SEL @ 1 km range** for individual surveys in logarithmic range bins. Panel a) shows values for 2D (circles) and 3D arrays (squares), the top curve shows the mean s.d. trend with log-range when using lumped data from all sources of > 1000 cui; the lower magenta curve shows the mean s.d. trend calculated for individual surveys and averaged in the log-range bins; the blue crosses are the s.d. of shot to shot variability in the log-range bins when using all data. Panel b) shows measured SEL with source volume, as measured at 1 km range (or as close to 1 km as the data set allows).

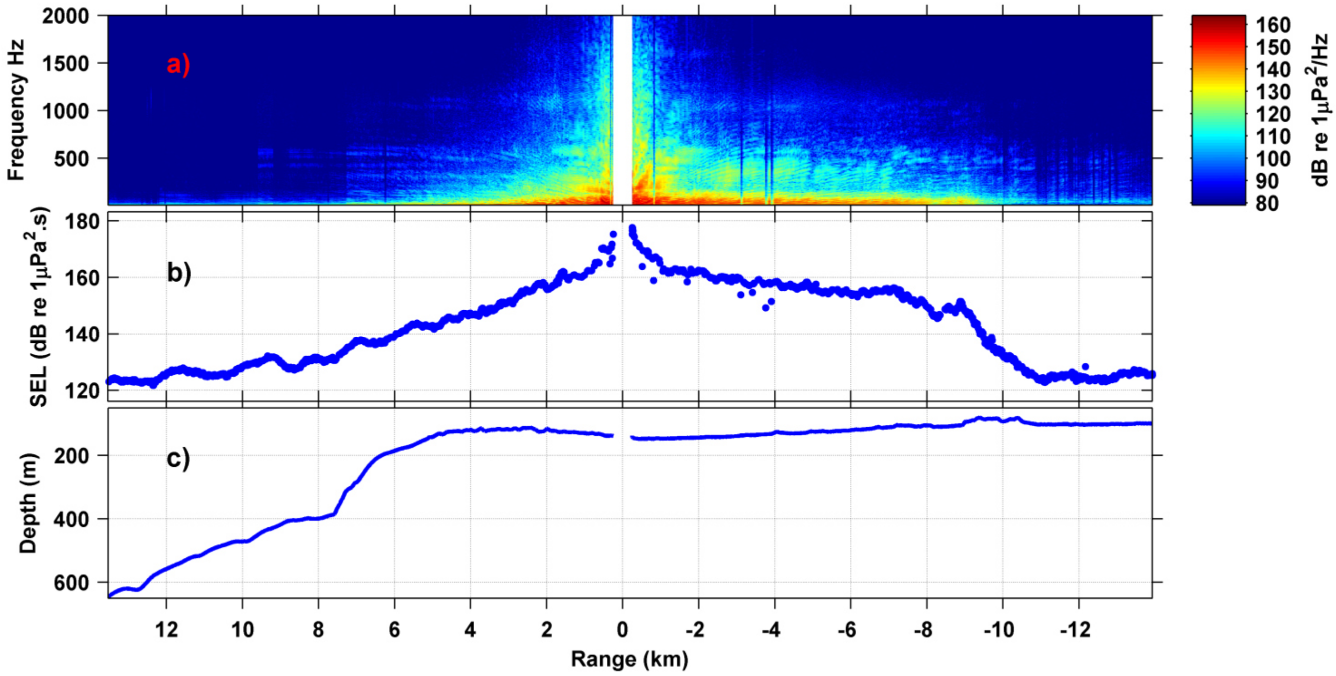


Figure 5: **Transmission of a 3040 cui source across shelf**, with a) frequency content for the source which passes within 180 m of a seabed receiver in 160 m of water with range from offshore (left) to inshore (right); b) sound exposure level measured for this survey line and receiver; and c), water depth along survey line.

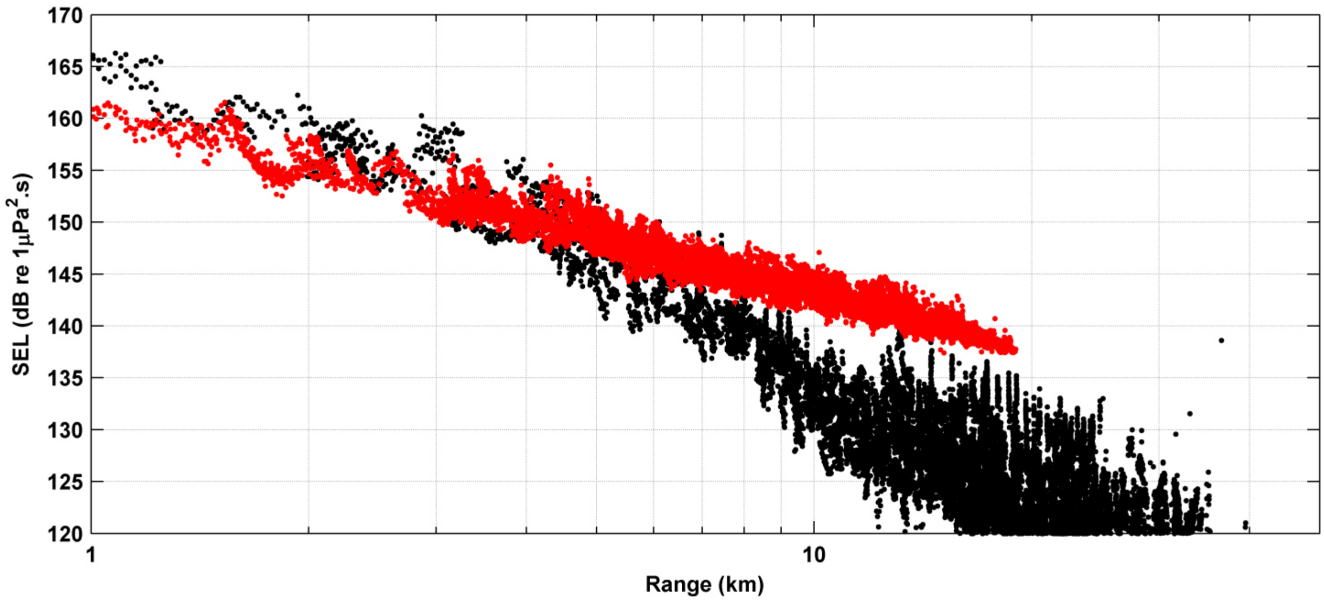


Figure 6: Comparison of 3147 cui (red, thick sand, 110-250 m water depth), and 3090 cui arrays (black, thin sand overlying limestone, 100-200 m water depth).

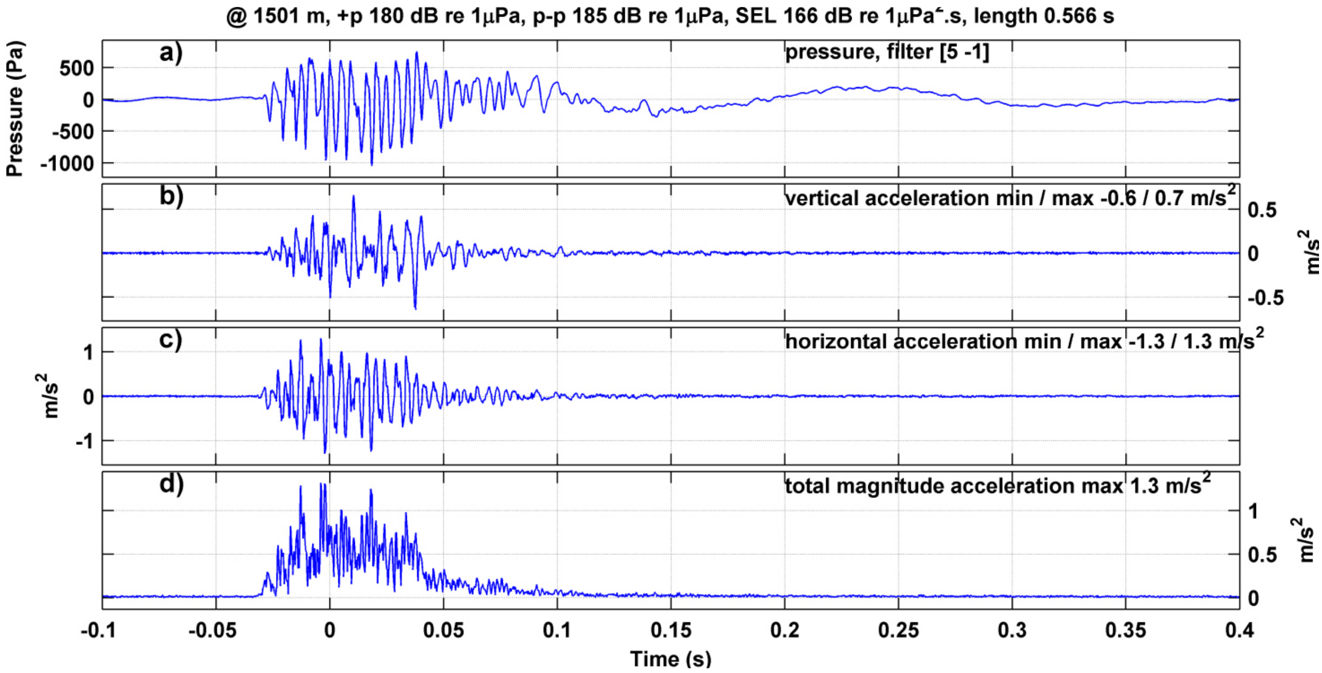


Figure 7: Waveforms of 3130 cui air gun signal at 1501 m range made in 39 m water depth, with: (a) pressure; (b) vertical seabed acceleration; c) horizontal seabed acceleration; and d) total magnitude of seabed acceleration.

## 4. DISCUSSION

The primary point of this paper has been to highlight several major features of air gun transmission in Australian waters and to present measured seismic source transmission curves with range. These issues are discussed only briefly below. Of note is that measurements of air gun transmission reflect the local environments and that some Australian marine environments are not well represented here, such as the possibly reflective seabeds of sand or sandy mud believed prevalent across northern Australia. Factors considered important here are:

1. There is large variability in transmission of signals from seismic sources around Australia even for similarly sized sources. This high variability implies that simplistic models and taking a source measured at location A and transferring it to location B are not necessarily valid unless the different environmental features impacting sound transmission are factored in;
2. Bathymetry profiles along transmission paths, sound speed profiles and how these vary with range and time, plus seabed types are critical factors for sound transmission. In general seabed types are not well defined for parameters pertinent to sound transmission in Australia at the continent scale (Baker et al. 2008);
3. Transmission in open ocean waters is considerably different to that in continental shelf waters and that up or down the continental shelf slope. This can be seen on Figure 5 where the steep shelf slope at 6-8 km rapidly attenuates signals transmitted from a source offshore up the slope to the receiver, whereas when the seismic source is on the shelf and the water relatively constant in depth, transmission is good;
4. In general signals from larger sources transmit further, but this is not always the case;
5. When comparing all seismic survey data, the mean standard deviation of received SEL at any range was 3-12 dB;
6. When comparing signals from within an individual seismic survey the mean standard deviation of received SEL at any range was 2-4 dB;
7. Shot to shot variability of the same source given by the mean standard deviation at any range of was 1-3 dB, possibly produced by the gun strings moving around in a seaway changing individual source locations,

particularly in the vertical. This will make little difference to a signal directed below the array but a large difference to signals propagating horizontally;

8. Commercial seismic sources less than 2500 cui generally will not exceed 160 dB re 1µPa$^2$·s at 1 km while larger arrays generally do exceed this value (important for mitigation measures);
9. In these data sets most seismic energy transmitted at low frequencies (< 500 Hz, Figure 5) with only low to modest levels of higher frequency energy experienced closer to a source (> 500 Hz, mostly at < 1 km), but this may not always be the case and will be dependent on sound transmission drivers of bathymetry, seabed type and sound speed profiles;
10. The prevalence of limestone or calcarenite seabed types in southern and Western Australia results in much higher signal attenuation rates when compared with transmission over sand (this is the cause of the different transmission regimes seen on Figure 6). The physical reasons for this are explored in Duncan et al. (2013);
11. A considerable amount of energy generated by seismic survey sources excites the ground directly or travels horizontally in and possibly along the seafloor (certain seabed types support interface waves). This signal energy may have implications for fauna living in or attached to the substrate.

## 5. ACKNOWLEDGEMENTS

The project could not have proceeded without the widespread support of a large number of companies within the petroleum industry. Thanks are owed to Mark McCallum and staff from the Australian Petroleum Production and Exploration Association who provided support for the synthesis presented here.

John Hughes of Santos Ltd. is recognised for his inspirational long-standing support of sea noise measurements and environmental studies as are; Don Kratzing, RocOil Pty. Ltd.; various staff at Woodside Energy Ltd.; Myles Hymas, Apache Energy Ltd.; BHP Billiton Petroleum; Origin Energy; Benaris; Essential Oil; PIRSA, GeoScience Australia; Shell; and BP Australia, all of whom have directly funded measures made here.

Data and support from the Joint Industry Programme on E&P Sound and Marine Life (JIP) managed by the International Association of Oil & Gas Producers (IOGP) has been used here (geophone data and 140 cui experimental source measurements). The principal contributing companies to the JIP programme are BG Group, BHP Billiton, Chevron, ConocoPhillips, Eni, ExxonMobil, IAGC, Santos, Statoil, and Woodside. The U.S. Bureau of Ocean Energy Management (BOEM), Origin Energy, Beach Energy, and AWE also provided support under the JIP programme.

Malcolm Perry and Frank Thomas of the Centre for Marine Science and Technology, Curtin University have been crucial in designing, building and deploying sea noise loggers. Andrew Levings assisted in many sea noise logger deployment and recovery exercises. We thank the many commercial fishermen whom have acted so professionally during gear deployment and recovery. GeoPro GmbH Hamburg collected one set of seismic records from the Victorian coast using their Sedis IV instrumentation, under contract to Santos.

## 6. REFERENCES

Baker, C., A. Potter, M. Tran, and A.D. Heap. 2008. Geomorphology and Sedimentology of the Northwest Marine Region of Australia. Report Number Record 2008/07. Geoscience Australia, Canberra. 220pp.

Duncan, A.J., Gavrilov A.N., McCauley R.D., Parnum I.M., Collis, J.M. (2013) Characteristics of sound propagation in shallow water over an elastic seabed with a thin cap-rock layer. J. Acoust. Soc. Am. 134 (1): 207-215

Halvorsen, M. B., Casper, B. M., Woodley, C.M., Carlson, T.J., Popper, A.N. (2012). Threshold for Onset of Injury in Chinook Salmon from Exposure to Impulsive Pile Driving Sounds. PLoS ONE. 7(6): e38968

Malme, C.I., Smith, P.W.Jr., Miles, P.R. (1986). Characterisation of geophysical acoustic survey sounds. OCS Study MMS-86-0032. Prepared by BBN Laboratories Inc., Cambridge, for Battelle Memorial Institute to the Department of the Interior-Mineral Management Service, Pacific Outer Continental Shelf Region, Los Angeles, CA.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J., McCabe, K. (2003). Marine seismic surveys: analysis and propagation of air-gun signals; and effects of exposure on humpback whales, sea turtles, fishes and squid. In (Anon) Environmental implications of offshore oil and gas development in Australia: further research. Australian Petroleum Production Exploration Association, Canberra, pp 364-521 available www.cmst.curtin.edu.au/publications (2001)

Nieukirk, S.L., Stafford, K. M., Mellinger, D. K., Dziak, R. P., Fox, C. G. (2004). Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. J. Acoust. Soc. Am. 115 (4): 1832-1843

Petkovic, P. & Buchanan, C. 2002. Australian bathymetry and topography grid. [Digital Dataset]. Canberra: Geoscience Australia. http://www.ga.gov.au/general/technotes/20011023_32.jsp (downloaded 2004)

Tashmukhambetov, A. M., Ioup, G. E., Ioup, J.W., Sidorovskaiab, N. A., Newcomb, J. J. (2008). Three-dimensional seismic array characterization study: Experiment and modeling. J. Acoust. Soc. Am. 123(6): 4094-4108

## 7. Appendix 1

A listing of hardware used in recordings is given in Table 1.

Table 1: Hardware used in recordings.

| Set | Hardware | Sampling |
|---|---|---|
| 2090, 2173, 2180, 2296, 2430, 2542 | DAT system - GEC Marconi SH101X hydrophones (typical sensitivity -204 dB re 1 V/μPa, capacitance 9.4 nF); to RANRL PA6511-A pre-amp.; to Sony DAT D8 tape deck used in long play mode (32 kHz sample rate) | 32 kHz continual, total system gain -20 to 40 dB |
| 2505 | Tattletale logger - General Instruments C-32 hydrophone, -200 dB re 1 V/μPa over the freq, range < 1 Hz to 3 kHz, capacitance of 0.45 μF; RANRL PA6511-A pre-amp.; Tattletale 7 (Greeneridge Science) based logger system writing to SCSII format hard disk | 90 s samples every 10 minutes at 10 kHz, 40 dB gain |
| 2542, 1625, 2627, 2608, 2609, 2615, 2629, 2632, 2669, 2670, 2675, 2680, 2703, 2707, 2708, 2710, 2736 | CMST-DSTO sea noise logger - Hydrophones - GI C32 (specs as above) or Massa TR1025-C (typical sensitivity of -195 dB re 1 V/μPa , capacitance 0.04 μF) or GEC Marconi SH101-X (specs as above) or HiTek HTI 90U (typical sensitivity -197 dB re 1 V/μPa, capacitance 13.8 nF); a modified RANRL PA6511 pre amp (-20 to 40 dB gain; to signal processing card, A-D converter sampled using Persistor processor writing 16 bit samples in IEE byte format to Flash card then to IDE hard disks (8-128 GByte). | Variable sample schedule, typically 120-300 s samples every 15 minutes @ 6 kHz but this variable, -20 to 40 dB system gain, 8 Hz low frequency rolloff applied |
| 2635-2649 | GeoPro Sedis IV – Benthos AQ-1 hydrophone (nominal sensitivity – 205 dB re 1 V/μPa, capacitance 14.5 nF) and pre-amp to Sedis IV 24 bit recording package, 26 dB gain, low freq roll-off, data to SEGY files in IBM byte format, these converted to IEEE byte format Matlab files | Continual, 500 Hz sample rate, 220 Hz anti-aliasing |