Near Source, High Frequency Air-Gun Signatures.

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Abstract

High frequency signatures of individual 60 cubic inch and 250 cubic inch air-guns were recorded at 10m from source during dedicated air-gun field trials. The high frequency recordings were made with a sample rate of 300 kHz and had a flat response from 20 kHz – 100 kHz. Recordings were low cut filtered at 20dB per decade below 20 kHz. Waveform traces were inspected and maximum pulse power was evaluated. These two air-guns were found to have substantial high frequency energy output up to 150 kHz. Maximum pulse power occurred close to the pulse onset, and ranged from approximately 170 dB re 1uPa^2 / Hz at 10 kHz (both air-guns) to approximately 120 dB re 1uPa^2 / Hz (60 inch air-gun) and 110 dB re 1uPa^2 / Hz (250 inch air-gun) at 100 kHz. Power levels are hugely in excess of deep ocean ambient noise across the entire spectrum. Spectrum levels at 60 kHz, uncorrected for low-cut filtering, were calculated to be 173 dB re 1uPa for the 60 inch air-gun and 178 dB re 1uPa for the 250 inch air-gun respectively. The low cut filtering crudely simulates the low frequency attenuation inherent in the dolphin auditory system, and hence these numbers can be taken as crude estimate of the over-hearing-threshold levels at 60 kHz. However, the maximum pulse power falls within a sufficiently small time window (~3ms) as to fall below the integration time of the dolphin auditory system, so further refinement would be needed. This paper demonstrates that the output of air-guns cover the entire frequency range known to be used by marine mammals, and do so at substantial energy levels. They will be clearly audible to most, if not all, members of the cetacea and pinnipeda. The potential for hearing damage will require further investigation.

Keywords: *Seismic, Air-Gun, Wideband, High Frequency, Source, Hearing, Dolphin.*

Introduction

As one of the more intense man-made noise sources in the marine environment, seismic exploration has been a topic of some interest and concern to scientists, in regard to its potential impact on marine mammals. As animals with well developed sensory systems, particularly sound, it is reasonable to assume that intense noises will interact in some way with marine mammals.

The effects of seismic surveys on marine mammals have been studied for about 3 decades (Richardson *et al*, 1995). Most study has focussed on the effects of seismic surveys on large mysticetes. This is a logical approach, since seismic air-gun arrays are configured for geological surveys, which require low frequency sound for deep penetration. Mysticete whales are expected to have well developed low frequency hearing ability, making them susceptible to seismic sounds. The fact that mysticete whales produce low frequency calls implies that they will also be able to perceive such calls, and further anatomic evidence suggests a funtional mapping of inner ear mechanical properties to low frequency sound reception (Ketten, 1994; 1998).

However, during the mid-late 1990’s it became apparent that the traditional view of seismic air-gun arrays as sources of low frequency sound was something of an over-simplification. This primarily came to light during acoustic dolphin surveys being conducted in conjunction with seismic operations, in order to explore occurrence and distribution patterns and the potential effects of such activity (Goold, 1996; 1998). The fact that dolphins were the target species during towed acoustic surveys meant that high pass filtering was employed to reduce unwanted engine and tow noises from survey recordings. The acoustic surveys keyed upon dolphin whistles, in this case common dolphins, *Delphinus delphis*, which are typically produced at frequencies upwards of 1 kHz. As the recording filters were set to roll off below some 3-6 kHz, far above the then published frequency ranges of air-guns of some 200 Hz, it was anticipated that very little air-gun energy would be recorded. The actual situation proved to be spectacularly different, and significant energies were recorded up to the limit of the recording system (22 kHz at that time). These air-gun signatures were later analysed and applied to dolphin hearing threshold data, which demostrated that such signatures were both wideband in nature and clearly audible to dolphin species out to several kilometres horizontal range from source (Goold & Fish, 1998). Since that time others have also recorded air-guns at high frequency and corroborated the existence of significant high frequency energy (Sodal, 1999).

The existence of these high frequency components in air-gun pulses broadens the range of marine mammals potentially affected by seismic activity. Whereas effects were once considered to be the exclusive domain of the low frequency mysticetes, it is now arguably the case that all families of marine mammals, including the high frequency specialists such as harbour porpoise, could be potentially impacted by seismic activity.

One of the problems involved with working with operating seismic surveys at sea is the relatively uncontrollable nature of recording such sources. A further complication is the fact that air-gun arrays are geometrically large and it is not possible to make point source measurements in the traditional manner. Distant recordings of air-gun arrays have to be made in the far field and then extrapolated/modelled back to source values. In addition, one is seldom afforded the opportunity to make specialist recordings of the output of individual guns within an array, particularly at close ranges to source.

In this paper we report on just such measurements, and explore the near-source, high frequency signatures of two individual air-guns, fired individually within an array.

Methods

Measurements were made of the output of two individual air-guns under controlled conditions at sea. The airguns were of 60 cubic inch and 250 cubic inch capacity respectively. Nominal operating pressure was 2000 psi and guns were fired on command.

The signatures were recorded through a custom built, multi-element array, containing benthos AQ4 and 12.7mm piezo-ceramic transducers. The array was configured with a stepped series of filters and gain levels across the channels, in order to keep system voltage levels within component operable limits within particular frequency bands. As high peak pressure levels were anticipated at low frequencies, the lower frequency parts of the array had less gain than the high frequency parts, to prevent voltage saturation of the electronics.

Sampling through the array was made at 300 kHz using a National Instruments Card interfaced with a high end PC. The channels in the recording array were sampled individually, in each case with the active recording element positioned at 10m range from the target air-gun. In this paper, only the highest frequency channel is examined. The high frequency channel had a flat response from 20 kHz to 100 kHz, with filter roll-off below 20 kHz of 20 dB per decade, and moderate transducer resonance between 100 and 200 kHz, peaking at about 6dB at 150 kHz.

Post processing analysis was conducted in MATLAB. Wavedata was visualised and plotted, and routines were implemented to investigate pulse power within the output pulses of each air-gun. Background noise was evaluated prior to the gun pulses and compensated for in the spectral analysis. Power spectral density analysis was conducted as a sliding series of hanning windows through the air-gun pulse from onset to tail, with the window being widened in powers of two until the maximum pulse power within a window was obtained.

Air-gun pulse spectra were plotted alongside idealised deep ocean ambient noise and dolphin audiogram curves for visual comparison. Pulse spectra were also used to yield spectrum levels of the respective pulses and provide a minimum equivalent loudness level at 60 kHz.

Results

Both air-guns had large signatures in the high frequency channel. Figures 1A and B show calibrated waveform traces of pulses from these two air-guns; note that the pressure axes are scaled in kilo-pascals. It is also interesting to note that there is a significant precursor to the main pulse, which is particularly evident in the 60 cubic-inch air-gun trace (Figure 1A). It is thought that this derives from the action of the solenoid and shuttle mechanism triggering within the gun at firing, producing a rapid mechanical transient pulse just prior to the main high-pressure air release.

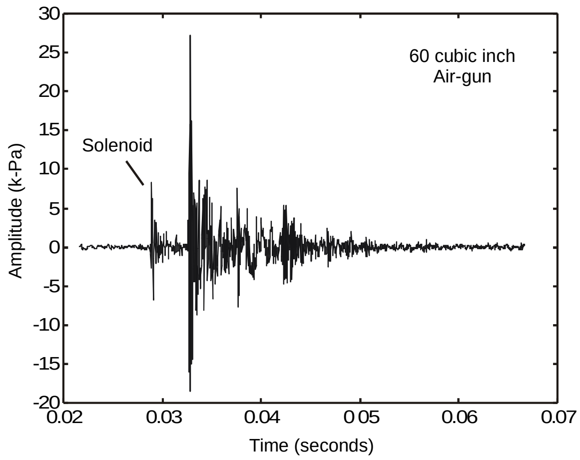

Figure 1A. *Waveform of 60 cubic inch airgun pulse. NB: solenoid precursor pulse. Amplitude scale in kilo-pascals.*

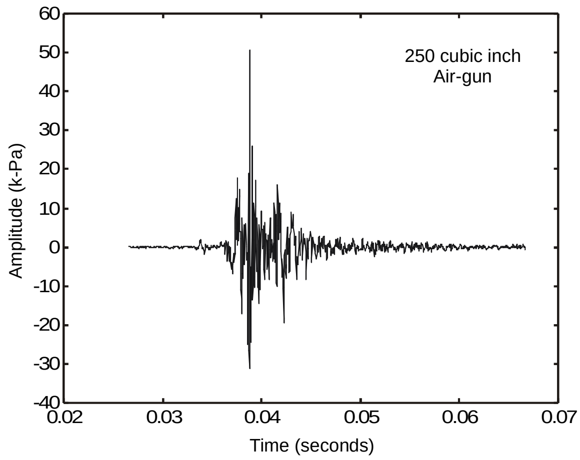

Figure 1B. *Waveform of 250 cubic inch airgun pulse. Amplitude scale in kilo-pascals.*

Power spectral density analysis yielded the plots in Figures 2A and B. In both cases the maximum pulse power is in excess of 110 dB re 1uPa^2/Hz across the entire spectrum from 0 – 150 kHz, although low frequencies dominate as might be expected. Idealised deep ocean ambient noise curves have been overlaid on Figures 2A & B in order to demonstrate how far above ambient noise levels the high frequency components of these air-guns are likely to be.

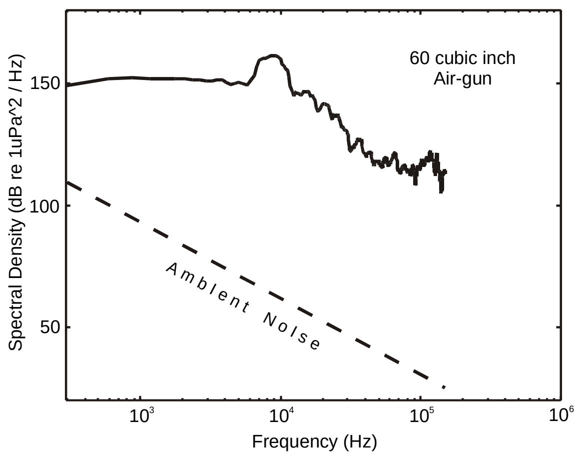

Figure 2A. *Maximum pulse power in the 60 cubic inch air-gun pulse. NB: frequencies below 20kHz are low cut filtered.*

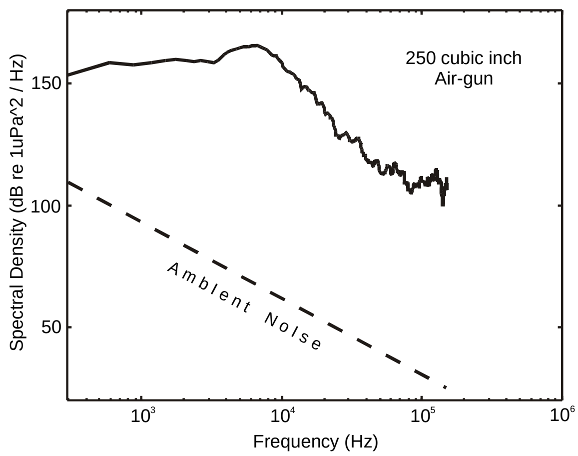

Figure 2B. *Maximum pulse power in the 250 cubic inch air-gun pulse. NB: frequencies below 20kHz are low cut filtered.*

Computed spectrum levels of these two pulses from 0 – 60 kHz yield figures of 173 dB and 178 dB re 1uPa for 60 and 250 cubic inch air-guns respectively. These figures are an under-estimate in real terms due to the low cut filtering of the recordings.

However, the low cut filtering approximates to the auditory filtering that occurs in the dolphin hearing system, and hence provides a useful estimate.

Figure 3 shows the pulse power spectral curve of the 250 inch air-gun again, but this time with an overlay of the standard tone-burst hearing threshold curve of the bottlenose dolphin (after Johnson, 1967) linked to the right axis. Although the power and toneburst units are not directly comparable, the overall levels and curve shapes nonetheless give an impression of the level of air-gun output over dolphin hearing threshold. Further, the spectrum level values give a crude estimate of the over-threshold level of these seismic pulses with respect to the bottlenose dolphin. Although a rather crude mechanism, the uncorrected spectrum level is acting in much the same way as the dolphin auditory system, by filtering the lower frequency components of the air-gun pulse (to which dolphin hearing is less sensitive) and passing the higher frequency components (to which dolphin hearing is tuned).

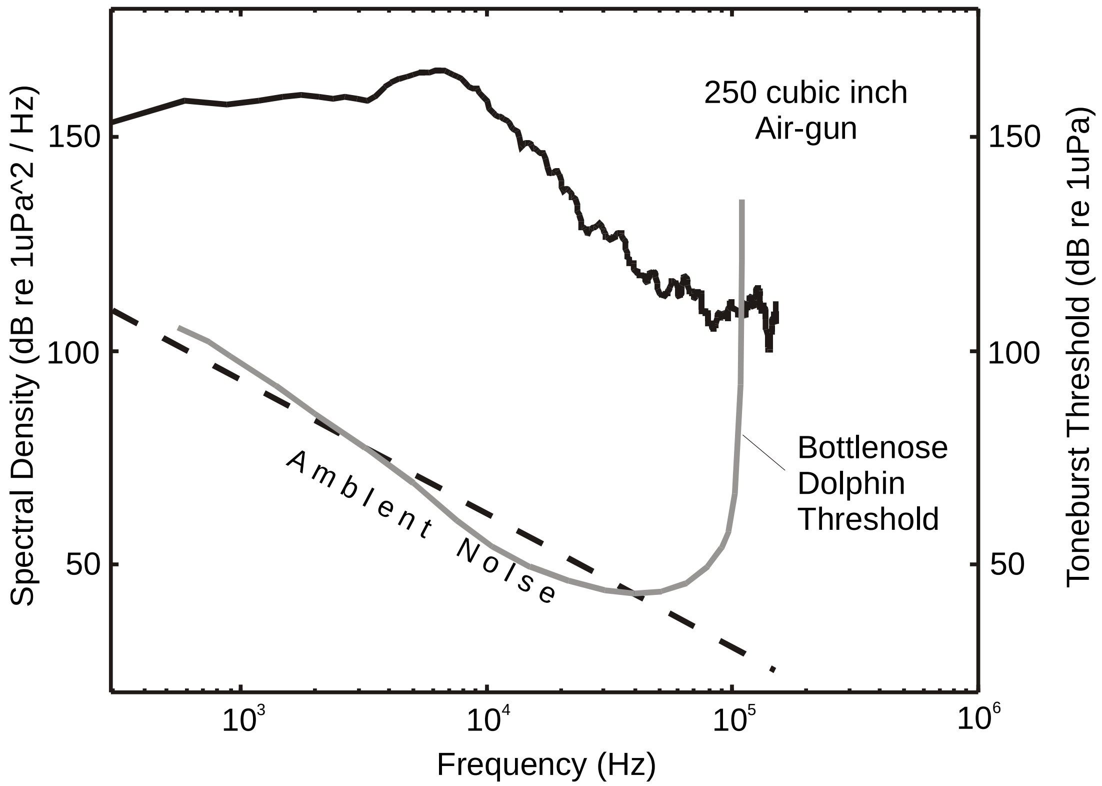

Figure 3. *Pulse power spectrum of the 250 cubic inch air-gun, with idealised deep ocean ambient noise and bottlenose dolphin toneburst hearing threshold curve.*

The spectrum levels at 60 kHz attempt to estimate equivalent loudness levels at that frequency, and put the seismic pulses approximately 133 and 138 dB above dolphin hearing threshold at that point. However, the maximum pulse power from which these estimates were obtained derived from an FFT window of approximately 3 milliseconds width, and hence below the integration time of the dolphin auditory system even at high frequency (Au, 1993). Integration time at 60 kHz would be approximately 20 milliseconds. The temporal summation aspect would need to be accounted for in a refined comparison.

Discussion

This paper clearly illustrates the audibility of seismic air-guns to even the most high frequency sensitive marine mammals. By expanding the bandwidth from 22 kHz in the original Goold & Fish (1998) work, to 150 kHz in this work, the extensive wideband nature of seismic air-guns is now clear. The output of air-guns spans the entire frequency range likely to be used by any marine mammal, and does so at considerable output levels, both above ambient noise and known dolphin auditory thresholds. The precise exposure levels and the implications of this will require more study and modelling, but over-threshold levels are clearly high and would likely remain so even if temporal auditory summation were accounted for. It is interesting to note that Finneran *et al* (2002) found masked temporary threshold shift to occur in a Beluga when exposed to seismic water-gun pulses of peak pressure 160 kPa (226 dB re 1uPa peak-peak, total energy flux of 186 dB re 1 uPa^2-s), although found no shift in bottlenose dolphin. Schlundt *et al.* (2000) found TTS to occur in bottlenose dolphins and belugas in response to 1-second tone bursts between 192 and 201 dB re 1uPa, and the animals began to exhibit altered behaviour at levels of 178 – 193 dB re 1uPa.

With regard to the air-guns in this study, dolphins would need to be within 10m or so of an individual air-gun to receive the pulse power levels illustrated. There are occassional anecdotes of dolphins ‘swimming in and out’ of active air-gun arrays during seismic surveys, although these remain largely undocumented. Whether this activity would be physically harmful to dolphins in the long term is unclear. There would also be a complex interaction of wideband sound fields within the air-gun array, since air-guns are seldom fired individually during operational surveys.

This paper is a first cut analysis of a considerable body of air-gun data obtained from controlled field tests. Here we merely seek to document the near source pulse signatures and spectral density levels of two selected air-guns, with reference to marine mammal audition. An extensive set of near-source and far field air-gun signatures, including individual guns, sub-arrays and full arrays, were recorded during the air-gun trials from which these recordings were taken. It is anticipated that these will form the basis of further documentary and exploratory work, and may provide information with which to model complex wideband sound fields within air-gun arrays in future.

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